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SATURN V, S-IC Y-RING ELECTRON BEAM WELDING SYSTEM

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WELDING DEVELOPMENT BRANCH

MANUFACTURING ENGINEERING LABORATORY

GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

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ABSTRACT

This report presents the development and verification of an electron beam system for joining S-IC Y-ring segments. The report is divided into four areas of 1) vacuum chamber, 2) electronic system, 3) tooling, & 4) weld evaluation.

The data obtained in the verification period at MSFC shows that the EB system is an improved and successful method of Y-ring joining. It is recommended that the system be used in the manufacturing of Saturn V, S-IC stage Y-ring.

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SATURN S-IC Y-RING ELECTRON BEAM WELDING SYSTEM

SUMMARY

PURPOSE AND OBJECTIVE

An Alternate, Back-up Means of Joining Y-Ring Segments

In the early phase of SATURN V, S-IC manufacturing planning, the metal inert gas (MIG) welding process was chosen for joining the three segments which make up the Y-Rings. The welding of five inch thick aluminum alloy 2219, to the quality standards of MSFC, required a lengthy period of technique development. The Manufacturing Engineering Laboratory initiated an alternate joining approach to be used in the event that the MIG process proved inadequate. That approach was an electron beam welding system.

The conception and subsequent development of the system, although prompted by the S-IC Y-Ring, represents the methods development mission of the R-ME laboratory.

Advance in Economy and Versatility

Several considerations prompted the move to more versatile and less time consuming joining processes. Electron beam welding fulfills the requirements with some added advantages:

1. The high power density of the electron beam has the potential of deep material penetration (3 to 4") with relatively low energy input per inch of travel. The result is greater weld joint efficiency (mechanical strength), higher quality, and a drastic reduction in the number of weld passes required.

2. A conventional vacuum chamber is impractical if the ring segments are to be completely enclosed. The logical answer is a local chamber, in the case of the Y-Ring, a split chamber. The welding system can be so programmed that segments machined to the finished Y-contour can be welded. The combination of the split chamber and the weld process programing makes the system fairly independent of ring diameter. Y-Ring segments can be finished machined in lengths practical on numerical control milling machines throughout the country.

3. The prevalent MIG process requires 50 weld passes per side of five inch thick billets, a total of 100 passes for each of three joints. Welding at the rate of four inches per minute, it takes approximately 30 hours actual welding time to complete a ring. However, by allowing time for interpass cooling, it takes 450 hours to deposit the 300 cubic inches of weld metal. An X-ray is taken after each few weld passes are made. This amounts to some 40 X-rays per joint, a total of 120 per ring. Additional time is expended in making, developing, and evaluating

radiographs and relaying the data to the welding group before succeeding weld passes can be made. In contrast, two fusion and two smoothing passes are needed with EB welding and five X-rays for each joint, making 80 hours per ring.

4. A fourth consideration is that the application potential of an EB system is much broader than the S-1C Y-Ring. It is feasible to consider using the highly efficient EB process in the assembly of cylinders, bulkhead fittings, composite structure, etc.

Contract Initiation

Several companies (approximately 8) were consulted on a Y-Ring EB welding systems. Not all considered the approach to be practical.

The maximum penetration of an aluminum alloy had been about 1/2 inch thick plates. Obviously, higher power densities were needed to penetrate the 2 1/4 inch section of the Y-Ring. The Sciaky Company was awarded a contract to develop, design, and manufacture a complete split chamber system. Several facets required development, to wit; local sealing around the Y-configuration; a higher amperage gun; cable insulation to prevent high voltage arc over; welding parameters and programing, etc. The Sciaky Company successfully developed the system on a laboratory basis. The background knowledge acquired advanced the science of EB welding, and has been applied by Sciaky in other installations, such as at Rocketdyne on heavy rocket engine components.

SYSTEM VERIFICATION

In 1963 the system was installed in the Manufacturing Engineering Laboratory, and a system verification program was conducted. The program started with plate panels, short Y-Ring panels, and culminated with the joining of three full size 120^{o} segments into a complete ring. In brief, it has been concluded that:

1. The mechanical portions of the system (including tooling) function properly and are adequate to accomplish the operation for which the system was designed, ie, electron beam welding the 33 feet diameter S-1C Y-Ring.

2. The electronic portion of the system operated satisfactorily. Only one problem area remains that should be given attention. This is the problem of high voltage arcing.

3. Evaluation of plate and Y-Ring EB weldments:

a. Heavy gage aluminum alloy 2219 can be electron beam welded satisfactorily up through 2 3/8 inch thickness employing a low voltage (30,000) EB welding system.

b. Significantly higher strength and joint efficiency can be developed in plate gages by the EB process than by either TIG or MIG welding, ie, ultimate tensile strength (TS) efficiency 70 to 80 per cent for EB welds and 50 to 65 per cent for TIG and MIG. So called "yield strength" for EB welds indicate an even more favorable situation.

c. Welds are quite ductile as evidenced by the measured reduction in area of 18 to 28 per cent on round tensile bars and by the necking of even the full thickness tensile specimen. Good elongation has been exhibited by cast and wrought metal within at least 1/2-inch of the weld.

RECOMMENDATIONS

The verification program at MSFC demonstrates the practicability and potential of the EB split chamber approach. As in any initiation of a process into component production, a period of technician orientation and process refinement is necessary. It is recommended, therefore, that:

1. The system be used to investigate, develop, and implement fabrication of the tee-stiffened Y-Ring.

2. Two distinctly different approaches be investigated simultaneously. The first approach is to develop techniques for welding the 5 inch thick billet. The second approach is to further refine the technique for EB welding Y-Ring segments that have previously been machined to final dimensions such as the tee-stiffened Y-Ring.

3. Other applications be considered to realize more fully the system potential.

INTRODUCTION

In the early stage of the S-IC manufacturing plan, the metal inert gas (MIG) welding process was chosen for joining the three 33 feet diameter segments which make up the Y-Rings. The welding of 5 inch thick material, to the quality standards of MSFC, required a period of technique development. The Manufacturing Engineering Laboratory initiated an alternate joining approach to be used in the event that the MIG process proved inadequate. The back-up approach was an electron beam welding system. Technical descriptions of the process and equipment development and of the system functional testing here at MSFC are the subjects of this report.

Although the MIG process has proved to be an acceptable means of joining the S-IC Y-Ring, it can be shown that the electron beam welding system has distinct advantages in economy and versatility.

The joining of large diameter rings, such as the S-IC Y-Ring, requires considerable time and cost if welded by the prevalent metal inert gas process. The MIG process requires 50 weld passes per side of five inch thick, 33 feet diameter rolled billets, a total of 100 passes each of three joints. Welding at the rate of four inches per minute, it takes approximately 30 hours welding time to complete a ring. However, by allowing time for interpass cooling, it takes 450 hours to deposit the required 300 cubic inches of weld metal. An X-ray is taken after each few weld passes are made. This amounts to 40 X-rays per joint, or a total of 120 per ring. Even more time is expended in making, developing and evaluating radiographs and relaying data to the welding group before succeeding weld passes can be made. In contrast, 80 hours would be expended by the EB system.

After the rectangular cross section ring has been MIG welded it is machined to the Y configuration. The 33 feet diameter ring already approaches the maximum capacity of boring mills. A 50 feet diameter ring would be beyond the range of any existing mill.

Considerations such as these prompted the move to more versatile and less time-consuming joining processes. Electron beam welding fulfills the requirements with some added advantages. The high power density of the electron beam has the potential of deep penetration with relatively low energy input per inch of travel. The result is greater joint efficiency (mechanical strength) higher quality, and a drastic reduction in the number of weld passes, only two fusion passes being required.

The conventional vacuum chamber necessary for EB welding is of course impractical if the ring segments are to be completely enclosed.

The logical answer was a local vacuum chamber, in the case of the Y-Ring, a split chamber. (Explained in detail in Section II.) In addition, the system is so programmed that segments machined to the finished Y-Ring contour can be welded. The combination of the split chamber and process programming makes the system fairly independent of ring size. The principal of a local chamber extends the application of EB welding. Certainly it is feasible to consider using the highly efficient EB process in the assembly of cylinders, bulkheads, fittings, composite structures, etc.

In the intital stage of planning, several companies (8 approx.) were consulted. Not all considered the approach to be practical. The maximum penetration of aluminum alloy had been about 1/2 inch thick plate. Obviously, higher power densities were needed to penetrate the 2 3/8 inch section of the Y-Ring. The Sciaky Co. was awarded a contract to develop, design, and manufacture a complete split-chamber system. Several facets required development which are treated in detail in the following sections, to wit; local sealing around the Y configuration, Section I; and a higher amperage gun and reduction of arcing, Section II. The tooling principles are related in Section III. Section IV contains an evaluation of EB weld parameters, soundness and strengths.

SECTION I. VACUUM CHAMBER

INTRODUCTION

Electron beam welding the 33 ft. diameter Saturn V Y-Ring predicated the development of the split chamber concept for joining large parts by the electron beam welding process. The basic difference between the split chamber and previous electron beam welding systems was that in the split chamber, portions of the part would extend outside the vacuum chamber during welding. This was done by making the chamber in two sections (split chamber) that could be closed around the parts to be welded. The mechanics necessary to effect the vacuum seals, move the chamber, position the electron gun, and evacuate the welding chamber will be discussed in detail.

DISCUSSION

Vacuum Chamber

The vacuum chamber consists of two halves. (See Figure 1.) The A half of the chamber is stationary and the B half of the chamber is moveable. The B section is backed away from the stationary section to permit placement of the workpiece or to allow access to the electron guns for maintenance or set-up purposes.

The B half of the chamber moves on a pair of precisely aligned rails. Precision in this part of the assembly is necessary to insure proper and repeatable contact at the A & B interface. Without proper mating, sealing would be virtually impossible.

The movable half of the chamber is operated by hydraulic power. Micro switches protect the chamber from damage due to excessive travel.

No difficulty was encountered in moving the B half of the chamber. Both the hydraulic mechanism and the mating were completely satisfactory.

Vacuum Pumping System

The vacuum pumping system is capable of evacuating the 52 inch by 52 inch by 42 inch welding chamber to an operating pressure below 1×10^{-4} mm Hg (.1 microns). The system consists of two different pumping systems operating in parallel. The first of these is a mechanical pump (Stokes, 300 CFM) which evacuates the chamber to 1×10^{-1} mm Hg (100 microns). The second is an oil diffusion pump (Consolidated Vacuum Corporation) which is valved into the system at 100 microns. Both pumps acting together then evacuate the chamber to the operating pressure of 0.1 microns.

The two systems are interconnected through a number of solenoid actuated, air operated valves. Valve actuation is controlled by a timing sequence which permits automatic pump-down of the chamber.

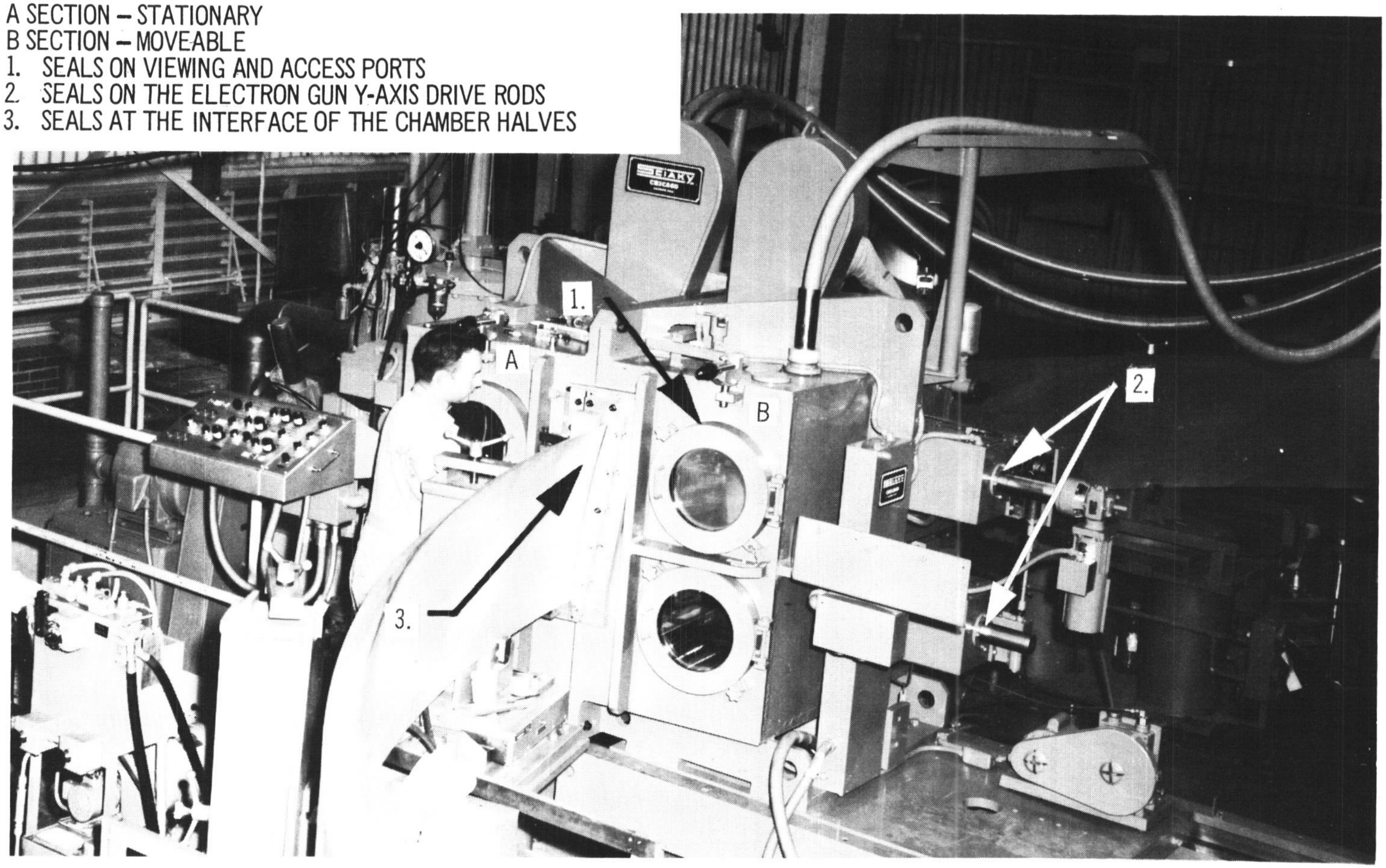


FIGURE 1. VACUUM SEALS ON THE SPLIT CHAMBER Y-RING WELDING UNIT

A third pump is employed in the vacuum portion of the electron beam welding unit. This is a small mechanical holding pump (Welch) which serves to maintain a vacuum on the diffusion pump outlet for a few seconds during the starting sequence. It is also tied into small diameter vacuum lines that aid in maintaining the vacuum seal where the electron gun Y-Axis drive rods protrude through the chamber wall.

Appendix A of this section describes the operating sequence of the vacuum pumping system and shows, schematically, the location of the various components.

The vacuum pumping system operated completely satisfactorily during the Y-Ring verification program. Under normal conditions the vacuum chamber was pumped down to operating pressures in 22 to 25 minutes after the start of the pumping sequence.

Vacuum Seals

Vacuum seals exist in many locations on the split chamber Y-Ring welding unit. The seals fall into three major categories:

1. Seals on viewing and access ports

2. Seals on the electron gun Y-Axis drive rods (sliding seals)

3. Seals at the interface of the chamber halves, including sealing of the Y-Ring where it passes through the chamber wall.

The locations of these seals are shown by arrows 1, 2, and 3 respectively in Figure 1.

Sealing of viewing and access ports is accomplished by the use of O-Rings (preformed packing) and machined surfaces. A light coat of Dow Corning High Vacuum Grease (a silicon lubricant) is applied on both mating surfaces and the O-Rings. The ports are closed and clamped by the light force of a manual nut. When pumping starts, the pressure differences between the outside and inside of the chamber provides the only force used to maintain the vacuum seal.

Vacuum seals on the viewing and access ports gave no trouble during the development and verification programs.

The electron gun Y-Axis driving mechanism requires four sliding vacuum seals. Each seal consists of two O-Rings (preformed packing) located such that the drive rod may slide without causing a leak. The area between the two O-Rings on each drive shaft is evacuated by the holding pump. This area is at a pressure of about 100 microns when the chamber is at the operating pressure of 0.1 microns. The system is shown schematically in Figure 2.

The operation of the sliding seals was satisfactory in all respects.

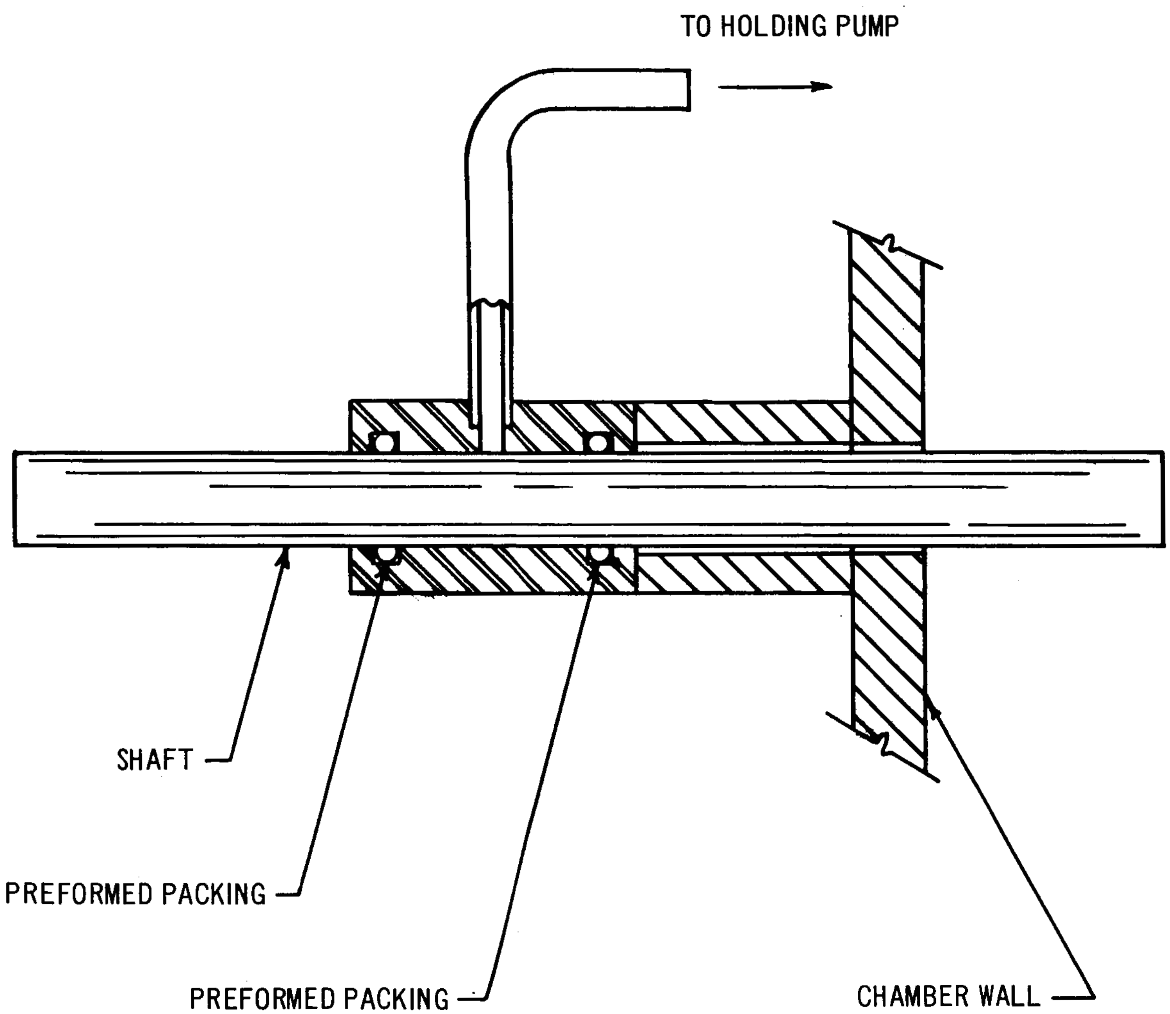


FIGURE 2. SEALING FOR THE ELECTRON GUN DRIVING MECHANISM

Sealing of the chamber at the interface of the two halves was accomplished using neoprene rubber strips between the machined mating surfaces. These are shown by the arrow in Figure 3. Sealing between the Y-Ring and the chamber was done through the use of metal blocks, rubber strips, and preformed packing (rubber O-Rings), Figure 4.

After chamber halves are brought into contact by the hydraulic power drive, four bolts, one at each corner, must be tightened in order for a seal to be established. This is one area that did prove to be troublesome during the Y-Ring welding program. During many of the pump down cycles, it became obvious that a leak existed somewhere in the system; quite often tightening of one or more of the four bolts corrected this condition. Normally leaks were too small to be audibly detected; thus, it was impossible to determine the specific cause of each leak encountered.

A similar type problem, to that mentioned above, was encountered with the system for sealing the Y-Ring. Small leaks were often corrected by tightening the clamping plates, yet the exact location of the leak could not be determined. By the end of the Y-Ring welding program, several of the rubber strip seals needed replacement. This was due to normal wear resulting from repeated use.

Sealing the Y-Ring to the vacuum chamber wall presented some difficulty. The problem was, as already mentioned, the existance of small leaks. On a few occasions it was necessary to completely dismantle the sealing apparatus and repeat the sealing procedures. This stopped the leaks; however, the location and cause of the leak still could not be determined. Sealing problems of this type sometimes required several hours to correct.

Gun Positioning

After the Y-Ring is positioned for welding by the locating and holding tools (discussed in Section III of this report) it is necessary to align the two electron guns so that the beams are centered exactly on the weld seams.

The vertical Z-Axis motion (maximum 30 inches) of the electron gun is accomplished by moving the gun carriage on a carrier nut and screw mechanism. Power to drive the screw is provided by an electric motor and gear train, both of which are located within the vacuum chamber. The speed of the electron guns can be programmed to vary between 0 and 100 ipm by using the vernistat control, discussed in Section II of this report.

Horizontal movement of the electron guns is limited to 1 inch in the direction perpendicular to the weld joint (X-Axis). This is also powered by an electric motor and gear train located within the vacuum chamber.

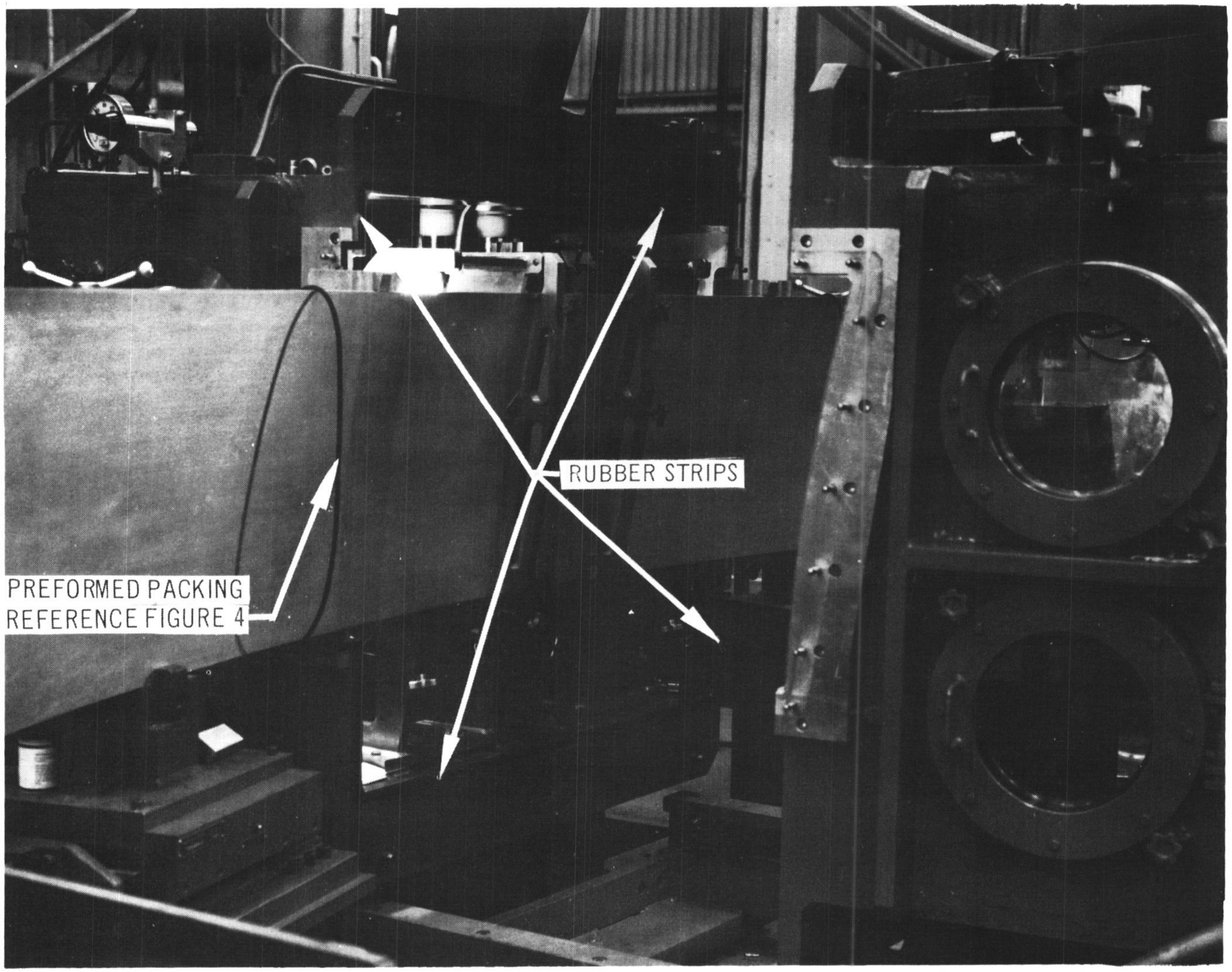


FIGURE 3. NEOPRENE RUBBER STRIPS BETWEEN THE MACHINED MATING SURFACES.

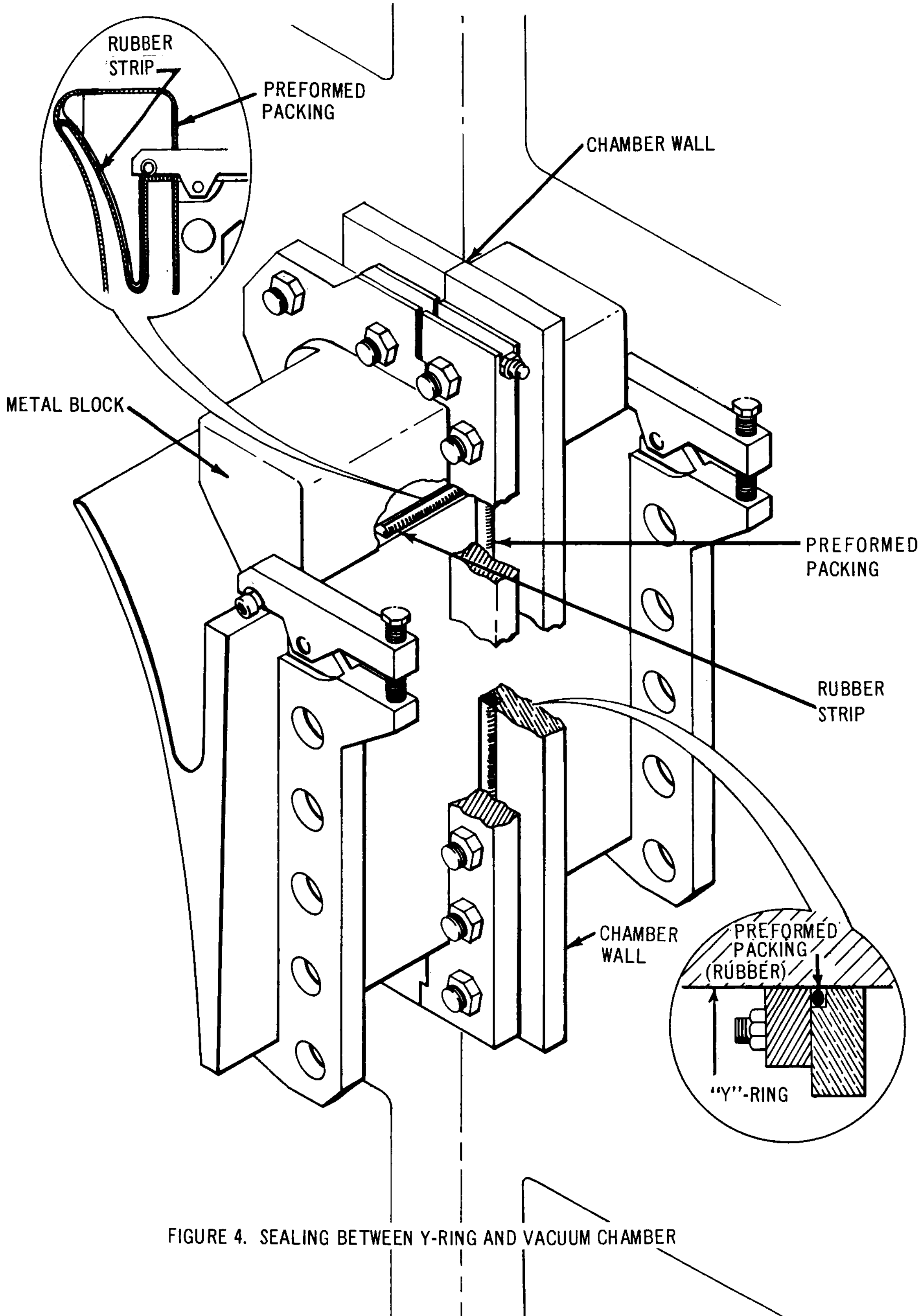


FIGURE 4. SEALING BETWEEN Y-RING AND VACUUM CHAMBER

The distance from the electron gun to the Y-Ring is controlled by moving the electron gun assembly. A gear reduction system actuates two operating rods which pass throught the chamber wall. (The sliding seals discussed earlier prevent leakage at this point.) One of these rods is attached at the bottom and one at the top of each electron gun assembly.

No difficulties were encountered with the systems used to move the electron beam guns. However, certain precautions must be followed concerning the location of the B section gun during opening and closing of the chamber. These are described fully by the operating instructions furnished by the equipment manufacturer.

Optics System

The optics system is used to align the electron beam gun to the Y-ring. The system for each gun is independent; however, the optics system for each is operationally identical. Each system consists of a high intensity light source to illuminate the weld zone, a stainless steel mirror mounted on the electron gun, a fiber optic bundle and associated lens system, a prism type reflector on the vacuum chamber, a telemicroscope to view the reflected image, and electrical controls on the operator's control panel. A detailed description and sketch showing how the alignment is accomplished is found in Appendix B.

The optics system functioned properly during all phases of the electron beam verification program.

CONCLUSIONS AND RECOMMENDATIONS

As a result of the work accomplished at MSFC using the split chamber electron beam Y-ring welder, it has been concluded that the mechanical portions of this system function properly and are adequate to accomplish the operation for which the system was designed, i.e. electron beam welding the 33 ft. diameter Saturn V Y-ring.

One area, though adequate, should be improved upon; this is the technique for sealing the chamber halves to each other and to the Y-ring. Suggested methods for improvement are:

1. Investigate other vacuum lubricants (for use on rubber seals and interfaces).

2. Investigate other sealing materials (to replace the rubber seals).

3. Investigate the use of thinner or thicker rubber seals.

4. Establish a rigid technique for tightening fasteners.

    a. Sequence

    b. Torque value

APPENDIX A. VACUUM PUMPING SYSTEM

There are two basic types of operation of the vacuum pumping system:

1. An initial start and final stop sequence

2. A start and stop during welding sequence

A step-by-step description of the two operations follows:

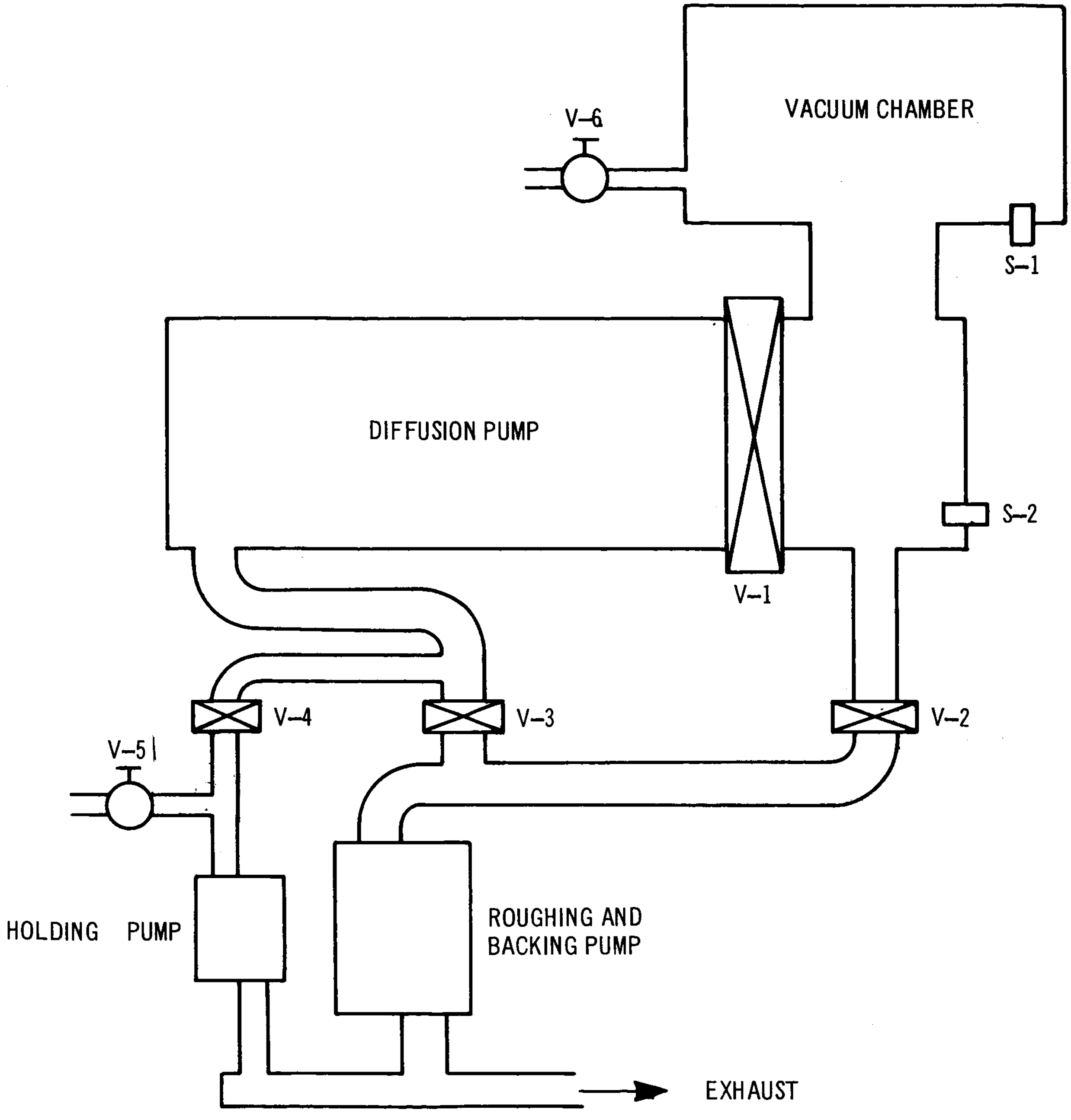
1. Initially, all valves are closed. Starting the system energizes the diffusion pump heater, the roughing pump motor, and the holding pump motor. After a short delay, the backing valve opens causing the roughing pump to back the diffusion pump while the oil is being heated. Figure 5.

After a time delay of 30 minutes the stand-by condition is reached. In this condition the backing valve is closed and the holding valve is open so that the holding pump backs the diffusion pump. The system is now ready for operation during the welding cycle.

To shut down (final stop) the system, the diffusion pump heater is de-energized and the poppet valve is closed. If the pressure is below 100 microns, the backing valve remains open. If the pressure is above 100 microns, the holding valve remains open. A thermostat, attached to the body of the diffusion pump near the heater, opens when the oil is cooled sufficiently. The pump motors are now de-energized and the valves return to the closed position.

2. At the start of the welding cycle, the START-STOP switch to evacuate the chamber is turned to "START". (The roughing valve and poppet valve switches should be in the "ON" position.) The roughing valve opens, connecting the roughing pump to the chamber. A thermocouple gauge measures the pressure in the chamber and, at a pre-set level, a relay is actuated which causes the roughing valve to close. After a short delay, the holding valve closes and the backing valve opens. After an additional short delay, the poppet valve opens. Now the diffusion pump, backed by the roughing pump, is connected to the vacuum chamber. The operating pressure is monitored by an ionization sensor tube mounted in the chamber.

At the end of the welding cycle, the START-STOP switch is turned to "STOP". The poppet valve closes. Air is introduced into the vacuum chamber (manual valve), the thermocouple gauge relay is de-energized, and the system returns to the stand-by condition. The roughing valve remains closed. The system is then ready for the next welding cycle.



V-1 HIGH VACUUM VALVE, POPPET*
V-2 ROUGHING VALVE, GATE*
V-3 BACKING VALVE, GATE*
V-4 HOLDING VALVE, POPPET*
V-5 VACUUM RELEASE VALVE, BALL, MANUAL
V-6 VACUUM RELEASE VALVE, BALL, MANUAL
S-1 SENSOR, ION TYPE
S-2 SENSOR, THERMOCOUPLE TYPE

*AIR OPERATED – NORMALLY CLOSED

FIGURE 5. SCHEMATIC LAYOUT OF VACUUM PUMPING SYSTEM

APPENDIX B. OPERATING SEQUENCE OF OPTICS VIEWING SYSTEM

Initial Set-Up

1. Retract B half of vacuum chamber

2. Set gun-to-work distance (established for Y-Ring welding at one and one-half inches).

3. Place a typewritten sheet of paper across the area of the Y-Ring seam. The purpose of this procedure is to make a test focusing of the objective lens and later of the telemicroscope.

4. The telemicroscope is not used until step 9. Viewing in the following steps, to step 9, is done through the optic fiber housing parts on top of the chamber. Figure 6.

5. All components of the viewing system should be checked for proper operation. This includes the operation of retractable prisms, lights, and light shields. Also determine that protective glass shields are in position on the objective lens of the fiber optic bundles.

6. Align image thru port with prism in chamber (A side), or periscope, (B side). A rectangular image will be noted. To bring rectangular image into focal plane, adjust by twisting the image end of the fiber optic slightly, but do not force.

7. Adjust the focal length of the objective lens on the gun end of the fiber optic bundle to provide optimum focus on the seam.

8. Adjust the iris (f stop) on the objective lens for adequate brightness of the image. Image brightness may also be enhanced by the use of the lamp brightness control on the operator's control panel.

9. Adjust telemicroscope to provide optimum focus by rotating knurled knob on top.

10. Adjust the eyepiece lens of the telemicroscope to sharpen the image of the reticle suitable to individual operators viewing.

11. Remove template and load and position Y-Ring sections in fixture.

12. Butt seam may now be viewed with clarity. Adjust seam image parallel to the horizontal cross-hair by rotating the entire objective lens body. Objective lens body is capable of 90 degrees rotation. (As butt seam is often of less width than the horizontal cross-hair, it is advisable to adjust the telemicroscope in the horizontal plane to place image parallel to horizontal cross-hair, but displaced by three or four markings on the reticle.)

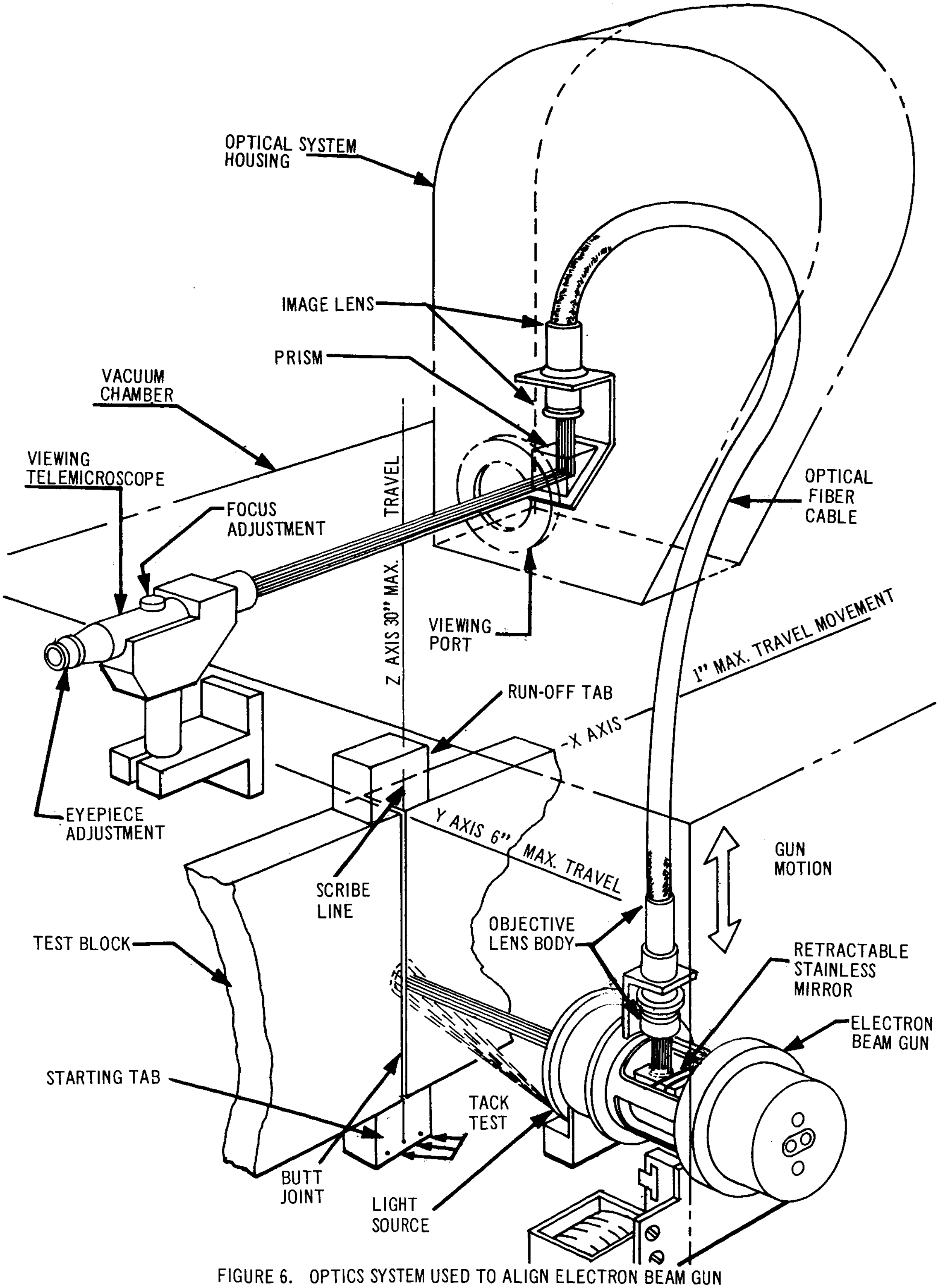


FIGURE 6. OPTICS SYSTEM USED TO ALIGN ELECTRON BEAM GUN

CAUTION: ALL GUN MOTIONS SHOULD BE MADE ONLY WHEN MOTION IS CONTROLLED BY THE VERNISTAT PROGRAMMER. THIS IS TO PREVENT THE GUN FROM CONTACTING THE WORK PIECE, THUS CAUSING EXTENSIVE DAMAGE TO GUN AND OPTIC FIBER CABLE.

Work Piece Alignment

1. Operate electron guns individually in the normal travel sequence to determine alignment of the gun travel with the butt seam. Any deviation in the location of the butt seam, as indicated by its image's deviation in the telemicroscope reticle, must be corrected by realigning the work piece. The distance between each marking on the cross hair represents about 1 mm or 0.040 inch on the work piece. With the seam parallel to the gun travel, the fiber optic objective lens must be adjusted to make the horizontal cross hair parallel to the seam. (See step 11 under Initial Set-up of Optical Viewing System)

2. Scribe marks on the upper and lower run-off tabs, should be made to coincide with the seam. The optical system is now set-up and will require no further adjustment except for adjustment of the telemicroscope eyepiece tc the operator's or viewer's eye.

Gun Alignment - Closed Chamber

NOTE: All ensuing operations are carried out with the CHAMBER CLOSED AND EVACUATED. Withe the gun travel now established the electron beam impingement point must be made to coincide with the seam.

1. With the scribe mark on the lower starting tab in view, (with the gun in the appropriate position to afford this view), press the "prism-out" switch, and perform a tack weld in the tab as a beam reference. The coordinate point indicated on the reticle is the point of beam impingement.

2. The gun is moved appropriately to make the point of beam impingement coincide with the scribe mark on the run-off tab. Another tack weld is performed as a check to insure that the beam is centered on the scribe line. Move gun to upper run-off tab and repeat the above tack weld operation. If the upper tack does not coincide with scribe line, the Y-Ring section must be re-aligned. After re-aligning, repeat steps 1 and 2, under Gun Alignment-Closed Chamber. When the upper and lower tack welds are aligned with the scribe marks and the seam, the weld operation may be started.

SECTION II. ELECTRICAL SYSTEM

INTRODUCTION

The electrical and electronic components utilized in the electron beam Y-Ring welding equipment perform or control all functions within the system. For the most part, components are standard items used in Sciaky electron beam welding units.

Due to the thickness of the Y-Ring, an electron gun having more power than any previously used had to be developed. This of course demanded that the power supply be made larger and that some modifications be made in the associated electronics. A major innovation in electron beam welding the S-IC Y-Ring configuration (continuously changing thickness) necessitated the use of automatic programmed control.

The power supply, electron gun controls, vacuum control system, electron gun operations, and high voltage arcing, are discussed in the following paragraphs.

DISCUSSION

Control of the electron gun is divided into two basic catagories:

1. Control of electrical functions

2. Control of mechanical functions (positioning)

Electrical Functions - Power Supply & Gun Controls

Electrical functions to be controlled consist of the high voltage which is applied to the anode, filament current which heats the emitter, or filament, focus coil current which controls the electron beam diameter at the work piece, and the beam current.

The high voltage is supplied to the electron gun by a high voltage cable which has its termination point inside the vacuum chamber. The voltage is controlled by means of a feedback signal from the high voltage rectifier which is compared to a reference signal generated by the high voltage adjustment control located on the operators control panel. Any difference in the two signals is sensed and appropriate adjustment to the powerstat is made via a Sciaky Dyne Motor Control Unit. This type voltage control is accomplished when the lock-unlock switch on the operators control panel is in the unlocked position. In the locked position the only means of changing the powerstat is by using the manual jog switch which also is located on the operator control panel.

The filament current is controlled by a powerstat which operates from a signal supplied from the manually positioned filament current adjustment pot.

The focus current is controlled by a constant current power supply. The signal to the power supply has two sources:

1. The focus adjustment pot on the operators control panel.

2. A feedback signal from the high voltage circuit.

The feedback control of the focus coil current automatically compensates for changes in the high voltage during welding.

The electron gun is designed to operate in a space charge limited mode. This then eliminates independent current control requirements. Being space charge limited, the beam current is proportional to the accelerating voltage to the 3/2 power.

No difficulties of a design nature were encountered in the controls of the electron gun.

The power supply used was built by Sciaky specifically for this unit. The only unique feature of the power supply is the high voltage switching arrangement which makes the changes required for operating either the 30 KW electron gun (A gun) or the 15 KW electron gun (B gun). The performance of the power supply was completely satisfactory.

Mechanical Functions - Vacuum Control & Gun Operations

The vacuum pumping sequence is controlled by the joint operation of mechanical timing devices and the signal obtained from the output of a thermocouple type vacuum gage. The diffusion pump and mechanical pumps are protected by appropriate pressure sensing switches in the water cooling lines and in the air lines which operate the various valves in the sytem. The vacuum pumping system operated satisfactorily during the verification program.

During the welding of a Y-Ring, three of the parameters are controlled by a Vernistat Adjustable Function Generator. These are high voltage, Y-Axis position, and X-Axis travel speed. The Y-Axis position control is used on the B gun only to control the distance between the electron gun and the work piece. The B gun welds the inside of the Y-Ring and needs the Y-Axis control to keep the work distance constant as it moves up the bulkhead leg of the Y-Ring.

The Vernistat Adjustable Function Generator is composed of two separate, but integral, units; a Function Adjusting Assembly, and an Interpolating Vernistat Potentiometer.

The Function Adjusting Assembly consists of an autotransformer which has a total of 101 equally spaced taps; these taps divide the input voltage into 100 equal voltage increments; a 34 pole, 101 position switch and a function adjusting panel.

Each function is set up by manually adjusting the positions of the sliders on the generator face panel. The panel is marked off in rectangular coordinates, with the output voltage as the ordinate and the shaft position as the abscissa, and provides a visual plot of the function.

The Interpolation Potentiometer consists of a series of commutator bars, which correspond to the sliders of the function adjusting generator, and a switching mechanism. Rotation of the shaft of the Interpolating Potentiometer switches the taps of the interpolating resistance element, one at a time, along the commutator. There are approximately three interpolations per shaft revolution.

Clockwise rotation of the Interpolating Potentiometer scans the function from left to right, i.e. from slider 1 to slider 34.

The control signal is compared to a feedbavk signal for the three functions and appropriate automatic adjustment is accomplished through the Sciaky Dyne Motor Control.

The Vernistat Adjustable Function Generator operated completely satisfactorily during the development program.

High Voltage Arcing

The two electron guns A and B used with the Y-Ring Electron Beam Welder were designed to operate at 30 KW and 15 KW respectively. Both guns operate at 30 KV; the A and B guns are rated at 1 ampere and 0.5 ampere respectively.

The guns operated satisfactorily only after much development effort. The problem with the electron guns was intermittent arcing of the high voltage inside the vacuum chamber. Improvements in the high voltage leads, insulators, and hardware design reduced the problem to a tolerable level. The most successful single design change that reduced arcing was the "boxing" of the beam. This consisted essentially of placing a box or plate on both sides of the part being welded. The result was a mechanical entrapment of metallic vapors and gases intiating from the workpiece.

The electron guns were made to operate in an acceptable manner; however, the problem of arcing was not completely eliminated.

CONCLUSION AND RECOMMENDATIONS

The electrical and electronic systems of the Split Chamber Electron Beam Y-Ring Welder are satisfactory.

One problem area remains that should be given attention. This is the problem of high voltage arcing. Changes in technique intended to further reduce arcing problems should be done in conjunction with application programs.

SECTION III. TOOLING

INTRODUCTION

The cross-section to diameter ratio of the S-IC Y-Ring is quite small resulting in a highly flexible ring. Handling, positioning, and machining are the major tooling considerations. In principle the tooling system employs (1) low friction, air bearing surfaces for handling, aligning, and rotating; (2) heavy duty, extremely rigid mills for joint preparation; and (3) accurate positioning and clamping of the segments within the vacuum chamber.

Mating of Y-Rings, in succeeding operations, to bulkheads or cylinders is readily done as long as the total inches in circumferences of two parts are nearly equal. Thus, in assembly of the Y-Ring, it is only necessary to control the length of the segments and to insure that the ring curvature is continuous across the weld joints. Consequently, the ring segments are restrained only near the ends where either a machining or welding operation takes place.

Machining the segment ends and positioning them for welding are critical operations. Uniformity of the joint is essential for predictable weld programing. Non-uniform openings, or gaps, would require changes in energy input. Because of the narrow width of the electron beam, it is important that the ring butting surfaces lie in the beam plane. Deviation by 1/4 of the beam width may result in an incomplete joint fusion. Joint preparation and positioning of parts are the two prime tooling considerations for electron beam welding.

The following discussion covers machining, support roller assemblies, air bearings, clamping, and installation.

DISCUSSION

Machining

The ends of the Y-Ring segments must be machined to close tolerances in order to produce quality welds. One end must be in plane to within $\pm$ 0.001 inch; it must be square to the base of the Y-Ring to within $\pm$ 0.005 inch over the full height of the Y-Ring (approximately 25 inches); and it must be true to the radial plane within $\pm$ 0.005 inch over the full width of the Y-Ring (approximately 4 1/2 inches maximum). The other end must be machined to allow no more than a 0.003 inch gap between the mating surfaces.

A system containing two router units was designed to satisfy the rigid machining requirements. (See Item 1, Figure 1). Each of the two units, one stationed at each end of the Y-Ring segment, is equipped with vertical travel routers. The Y-Ring segment ends are rigidly

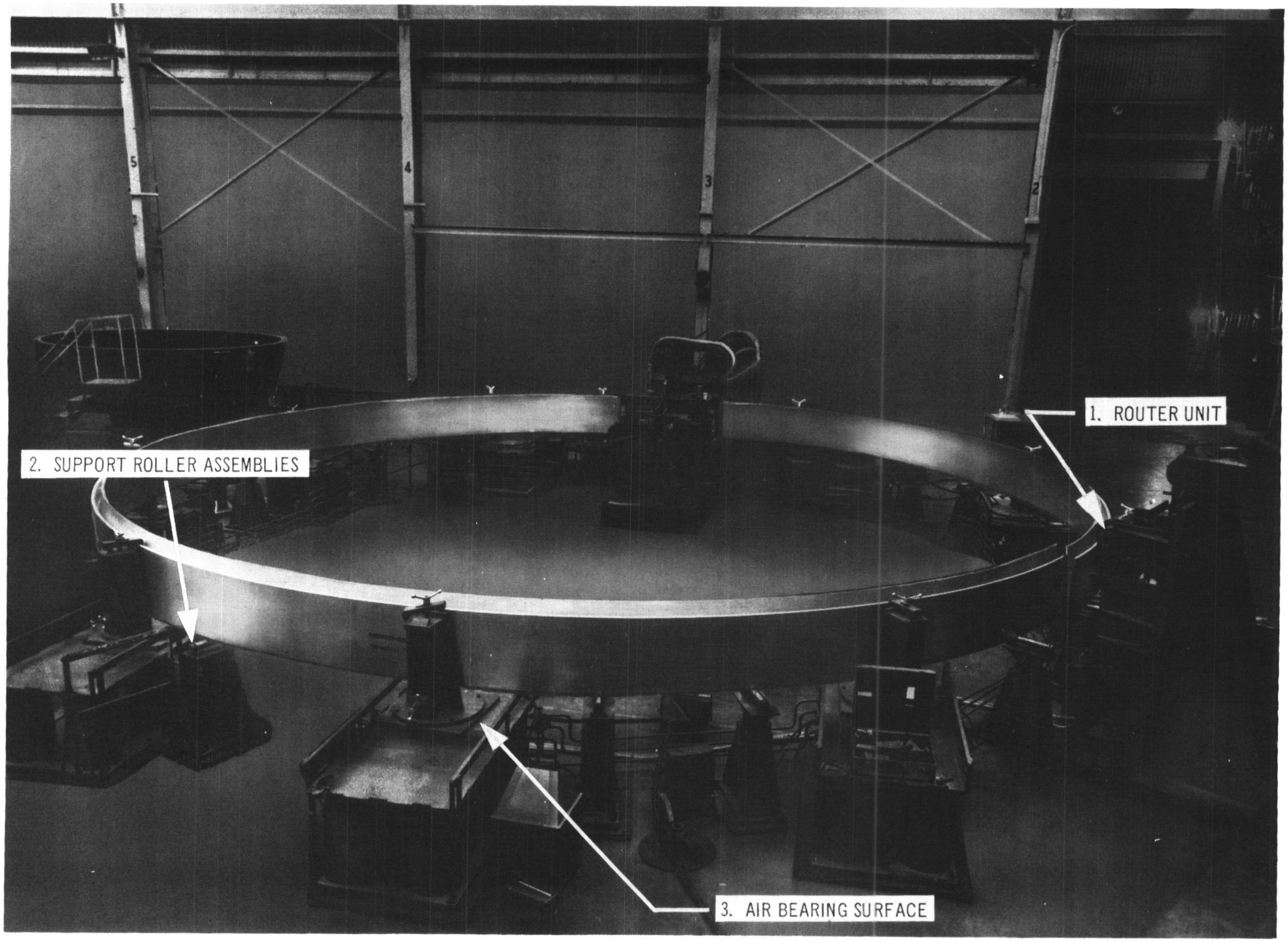


FIGURE 1. EQUIPMENT LAYOUT FOR ELECTRON BEAM WELDING Y-RING

clamped adjacent to the surface to be machined. After one end of the Y-Ring segment is machined, a pie-tape measurement is made to determine arc length requirements for machining the other end.

Support Roller Assemblies

The roller assemblies were designed to support and maneuver the Y-Ring segments into approximate position for machining and welding. Vertical actuation of the assemblies raises the segments permitting them to be rolled around the path of the fixture. All 16 of the roller assemblies are simultaneously operated, holding the segments in a single horizontal plane. (Item 2, Figure 1).

Air-Bearing Surfaces

The air-bearing surfaces are used for final positioning and alignment of the Y-Ring segments for machining and welding. (Item 3, Figure 1). When air supply is applied, they hold the Y-Ring segment in a level plane; a gap of approximately 0.002 to 0.005 inch being maintained between the air-bearing pads and the support surfaces. The Y-Ring segment is placed on the air-bearing pads and clamped, after which the pads are pinned in place on the support surface by locating pins. Three such surfaces are used to support the Y-Ring segment at the machining stations. (Figure 2). After machining of the Y-Ring segment ends, the clamps are disengaged, and the Y-Ring segment is maneuvered back into the original position over the roller assemblies and the sequence is repeated. After machining of segments, air-bearing surfaces are used to locate the weld joints of the Y-Ring against a gage block in the split vacuum chamber.

Clamping

The Y-Ring segment is rigidly clamped adjacent to the ends to hold the machine surface steady while being machined, and is supported by three air-bearing surfaces. While welding, the segments are rigidly clamped inside the chamber to hold the weld joints within tolerance. Each of the Y-Ring segments is clamped at four places outside the chamber by the use of three air-bearing surfaces and one stationary clamp stand assembly, which is adjustable heightwise, and sidewise. (Figure 2). Thus the segments are rigidly restrained only near the weld joint.

Installation

The Y-Ring machining and welding fixture consists of two router units, two clamp stand assemblies, nine air-bearing surfaces, 16 hydraulically-operated support roller assemblies, and four construction ball assemblies. Reference Sciaky Brothers, Inc. drawings E-F-5406 and E-F-5317, not included in this report, for installation of the split vacuum chamber. A concrete foundation is required for the components of the Y-Ring machining and welding fixture. The floor plates should have standard J anchors attached to ensure a stable foundation, and located to the dimensions given in Figure 2. The components of the fixture should be optically located on the floor plates to the dimensions given in Figure 2.

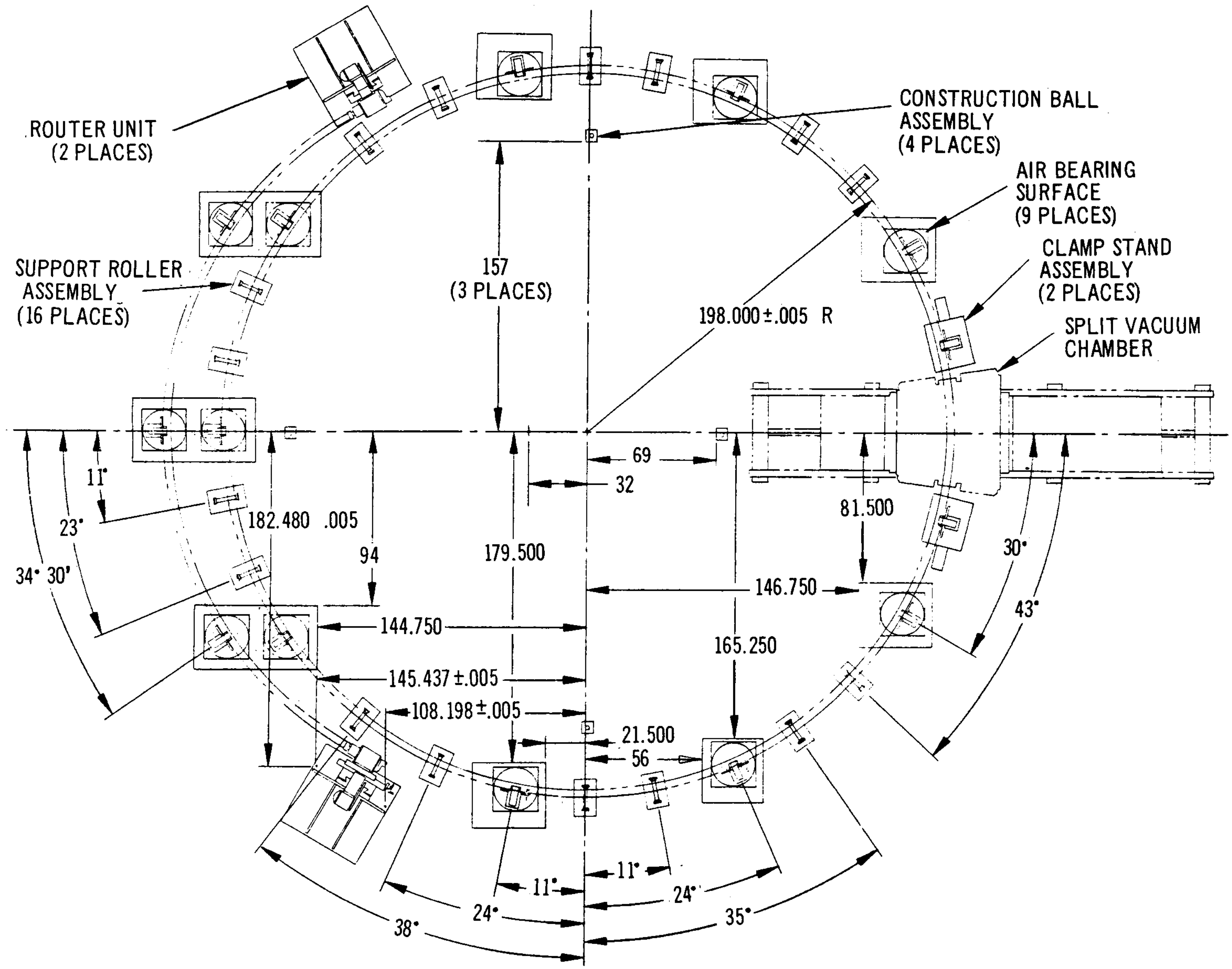


FIGURE 2. DIMENSIONAL LAYOUT OF TOOLS USED TO ELECTRON BEAM WELD Y-RING

Leveling screws are provided at the base of each component. Epoxy can be used to seal the opening between the floor plates and the base of the components.

CONCLUSIONS

The tooling system for machining welding functioned satisfactorly in the EB welding verification program. Handling problems were reduced to a minimum by the use of the roller assemblies for rotating purposes, and the air-bearing surfaces for final positioning and alignment of the Y-Ring; thus, reducing manpower cost requirements.

REFERENCES

Drawings

a. Fuel and Oxidizer Tank Y-Ring Joint Machining and Welding Fixture	GMT-13487 ME Lab MSFC
b. Front Base Assembly	Sciaky Brothers, Inc. Drawing No. E-F-5317
c. Rear Base Assembly	Sciaky Brgthers, Inc. Drawing No. E-F-5406

SECTION IV. WELDING EVALUATION

INTRODUCTION

Welded joints in heavy gage wrought aluminum alloy material are generally considered to develop low joint efficiency in the as-welded condition. This conception is based on the facts that (1) the heat of welding lowers the strength of wrought aluminum in all tempers other than annealed (-0), and (2) the cast or weld metal generally develops lower strength than wrought metal. Welding heavy gage material usually requires multipass welds, the number of passes generally increasing with gage, and thereby multiplying; (1) the possibilities of encountering weld defects, (2) the time consumed in welding and inspection, and (3) control precautions to minimize distortion. Hence, any welding process that either, (1) provides increase in joint strength or, (2) requires fewer passes, holds considerable advantage for welding heavy gage aluminum.

The electron beam welding process was believed to (1) have potential for developing high strength welds in aluminum in that the process should minimize the effect of heat of welding on the wrought metal and improve the metallurgical characteristics of the cast weld zone and (2) to require fewer passes due to the high depth of penetration per pass.

Interpretation of results obtained with electron beam welding, or any welding process, involves an understanding of the inherent characteristics of the materials being joined. For instance, in fusion welding aluminum, an easy way to show 100 per cent joint efficiency is to employ annealed (-0) temper material. In this temper, the minimum strengths of the material are developed --- that is the very intent of the thermal treatment employed in producing the -0 temper. Hence, to develop lower strengths in a joint than in the parent annealed material, where cast strength matches -0, it is practically self-evident that an obvious "defect" must be associated with the weld. On the other hand, it is not easy to develop 100 per cent joint efficiency for fusion welds in cold worked or heat treated tempers of wrought aluminum alloys even with sound or "non-defective" welds. This also is readily understandable since it is recognized that the heat of welding counteracts or destroys the effect of cold work and/or thermal treatments employed in producing the various -H___ and -T___ tempers that develop maximum strength for aluminum alloys. Generally, the higher the strength of the aluminum alloy being welded, the more sensitive the alloy to the detrimental effects of the heat of welding.

Aluminum alloy 2219 is basically a binary Al-Cu alloy and thus is heat treatable. However, the alloy also shows a definite response to cold work and hence properties of 2219 result from thermal treatment and/or cold work. Strengths in the -0, -T42, and -T62 tempers depend upon thermal treatment alone while strengths in the -T31, -T37, -T81, and -T87 tempers depend upon a combination of thermal treatment and cold work. Obviously, properties can vary with actual chemical analysis --- higher strengths being associated primarily with higher copper content within the specified range of 5.8 to 6.8 per cent. Actually, 2219 is a highly super-saturated alloy as it contains considerably more copper than can be retained in solid solution. (5.65 per cent Cu is soluble in Al at the solidus temperature of 1018^{o}F, under equilibrium conditions.) The strengths attained in the -T3___ and -T8___ tempers are derived in part from Cu held in solid solution and in part from Cu that is precipitated as finely divided particles throughout the microstructure. Precipitation or artificial aging is effected by heating under controlled conditions. The heating or aging time and temperature employed are related to the amount of cold work previously introduced so that a balance is attained between the Cu retained in solid solution and that precipitated, in order to avoid excess precipitation or overaging --- wherein strengths are lowered.

Fusion welding very simply being a temperature-time reaction is expected to lower the strength of the parent metal adjacent to the weld itself --- the cast nugget resulting from solidified liquid metal. The amount that strengths are lowered (magnitude of loss) and the expanse of area involved in the change (extent of loss) are related to the amount and distribution of thermal energy involved. The temperature distribution in material heated by welding depends on the thickness and width or configuration of the part, location of weld in the part, speed of welding, and the heat input due to welding. With a minimum amount of molten metal and minimum time involved in welding, less heat is absorbed by adjacent metal. Conversely, the larger the volume or cross section of molten metal involved at a given time, the greater the amount of heat to be extracted during solidification, thus the longer the time the adjacent metal remains at a high temperature, the greater resultant loss in strength, and the greater the distance from the weld that strengths are affected. Loss in strength is a great waste and imposes restrictions on effective use of high strength aluminum. An ideal situation for welding would permit rapid concentration of energy on the surfaces to be welded such that only a thin film of metal would be melted and little, if any, heat lost to the adjacent metal. EB welding, with its high intensity heat source, approaches these conditions.

The absence of Mg is a significant factor contributing to the good fusion characteristics of alloy 2219. This is one of the few aluminum wrought alloys that does not contain Mg. Early investigational work on EB welding demonstrated that the power required to penetrate 2219 was considerably greater than for other aluminum alloys. An explanation for this fact, is that 2219 has a somewhat lower vaporization potential similar to alloy 1100. This could be related to the absence of Mg in these alloys --- Mg being known to lower the triple point (solid-liquid-gas) and thereby raise the vaporization potential of a system. Since in EB welding the jet of vaporized metal may provide the pressure on the "puddle" to penetrate the material being welded, metal vapor plays an important role in this welding process.

It is obvious now from the above that EB welding requires consideration of different characteristics of materials than do TIG or MIG welding. Conductivity, and especially vaporization, assume new roles. The EB process has much to offer, but at the same time, more should be learned in applying the process and in evaluating the quality and performance of the joints obtained.

Objective

The objective of this evaluation of EB welds in various gages of aluminum alloy 2219 plate and Y-configuration was:

1. To establish the relation between process and material variables and their effect on joint integrity based on metallurgical and mechanical property test analysis.

2. To verify the validity of the parameters originally selected for welding the variable gage Y-configuration.

DISCUSSION

EB Welding Process Variables

Weld penetration in electron beam welding is strongly dependent upon beam power which is the product of the accelerating voltage times the beam current. Welding parameters normally to be set are accelerating voltage, focus coil current, welding speed, and gun-to-work distance. These variables affect overall weld contour or profile of electron beam welds.

Visual examination of weld contours developed by varying weld settings indicates that a narrow, nearly parallel-sided weld is desirable. This contour appears to coincide with the most effective use of energy in obtaining full penetration in heavy gage aluminum plate. Control of energy input is important in EB welding as in other welding processes. The goal is to employ just adequate high intensity energy to attain full penetration combined with controlled metal movement to form relatively smooth face and penetration beads. When metal movement created by the jet of vaporized metal is too violent (i.e., too high power density), the turbulence results in rough exterior weld surfaces having jagged hills and valleys and non-continuous interior surfaces characterized by frozen-in pockets or voids similar to cold shuts in castings. Porosity may occur along with other discontinuities and any of these defects may be associated with a momentary interruption of the electron beam, a near arc-out or an arc-out.

Weld Evaluation

Evaluation of weld quality of EB welded 2219 plate was made by visual, radiographic, and metallographic examinations, tensile, bend, and hardness tests. Visual examinations included inspection of weld bead contours; for penetration, smoothness, underfill, undercut, etc.; for evidence of discoloration from metal vapor deposit; for mismatch, misalignment, and distortion; and for conditions at run-on and run-off tabs. All panels were radiographed prior to sectioning for subsequent tests. Machined tensile and bend specimens were radiographed at two angles --- parallel to weld and 90° to direction of weld --- in an effort to locate more accurately any defects or reveal any unusual conditions prior tc testing.

Weld tensile tests directly related to the EB welding system for the Y-Ring consist of the following to date:

Chamber	Laboratory		Split Chamber, 30 KV Machine					
Welded	Sciaky		Sciaky		MSFC		Total	
Plate Gage	No. of Panels	No. of Specimens	No. of Panels	No. of Spec.	No. of Panels	No. of Spec.	No. of Panels	No. of Spec.
1/2"	10	42	3	24	1	8	4	32
3/4"	4	26	-	--	-	-	-	--
1"	1	3	-	--	-	-	-	--
1 1/4"	2	22	2	23	2	14	4	37
2 3/8"	2	23	1	18	1	17	2	35
Plate totals	19a	116	6	65	4	39	10	104[b]
Y-Panel	--	---	1	9	3	29	4	38[c]
Grand total	--	---	7	74	7	68	14	142
Y-ring	--	---	-	--	2	16	16	158

a = 17 of 19 panels were welded 6 inches by 6 inches. All plate panels in split chamber were welded 36 inches by 20 inches and Y-panels were 48 inches by 24 inches.

b = 36 of 104 tensile specimens were full thickness specimens 1 1/2-inches or 2 1/2-inches wide in the gage.

c = 31 of 38 tensile specimens were full thickness specimens 1 1/2-inches wide in the gage.

Metallographic examinations were made of sections from various locations in the welded panels and of selected specimens representing different welding conditions and/or demonstrating significantly different test results.

Test results are related to welding and test variables employed, i.e., power input, etc., to type test specimen, to plate gage, and to the particular lot of material employed.

Plate for Weld Property Evaluations

Aluminum alloy 2219-T81 plate, 1/2-inch to 5-inches thick and -T87 temper 1/2-inch to 2 3/8-inches thick (Table I) were employed for various weld tests. Chemical analysis, gas content, and tensile properties were determined for the material EB welded as 36-inch by 20-inch panels. Tensile properties of the heavy plate were determined at various locations across the thickness and from the variable thickness Y-configuration machined from the 5-inch plate to compare with the welded specimens from similar locations.

Welding Procedure

Joint Preparation

Plates were square butt welded employing machined abutting edges. Parts were chemically cleaned, solvent wiped, and finally abutting edges and adjacent surfaces were scraped just prior to positioning in the chamber fixture. Plates were matched and aligned as closely as possible and a tight fit was attained by the clamping fixturing. Run-on and run-off tabs were tack welded onto the ends of the large panels.

Weld Parameters

Various weld settings were employed for test plates, as shown in Table II, for constant thickness material. These settings resulted in adequate penetration with some variation in weld profile, depending upon beam power input, welding speed, and focus amperage for a given gage. Settings selected for thorough evaluation provided a nearly-vertical-sided weld profile and approximately the same weld width for all gages. The values for constant thickness plate were employed in programming settings for the variable thickness Y-contour where the constant weld width was considered to be desirable to control shrinkage distortion.

Finishing Technique

A finishing technique to overcome the hill-and-valley contour characteristic of electron beam welds in plate consisted of partial removal of the bead by machining, followed by a low-powered, defocussed beam smoothing pass. No filler metal was employed in large panels.

Test Procedures

Visual and radiographic inspection of panels preceded layout and sectioning according to a precise plan (note markings on plate in Fig. 3) such that the identity of each specimen was retained with its location in the original weld. Likewise tensile and bend specimens machined from the panels were so orientated, when radiographed "sideways", to locate conditions on the face vs. the root side of the weld.

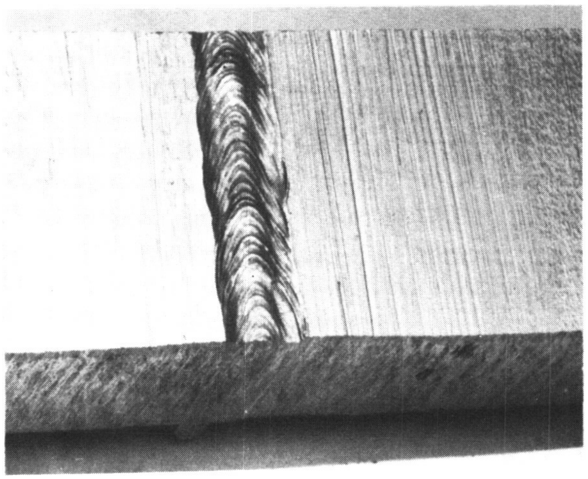
Tensile specimens included: (1) full thickness slices 0.090-inch to 0.50-inch wide, parallel-sided, from the small panels (6 inches by 6 inches); (2) 1/4-inch or 1/2-inch diameter round specimens from various locations (layers) across the weld thickness; also (3) 1/2-inch thick flat sheet-type tensile specimens from face, root and center locations (layers) across weld thickness; and (4) full section tensile specimens 1 1/2-inches or 2 1/2-inches wide in the gage length. Elongation was measured on face, root and edge of specimen, using gage lengths of 1/8 inch to 2 inches to determine local elongation in the vicinity of the weld and the effect of a smoothing pass on local elongation. Standard AWS face, root, and side bend specimens were bent; noting load to failure, angle of bend, and elongation on tension surface.

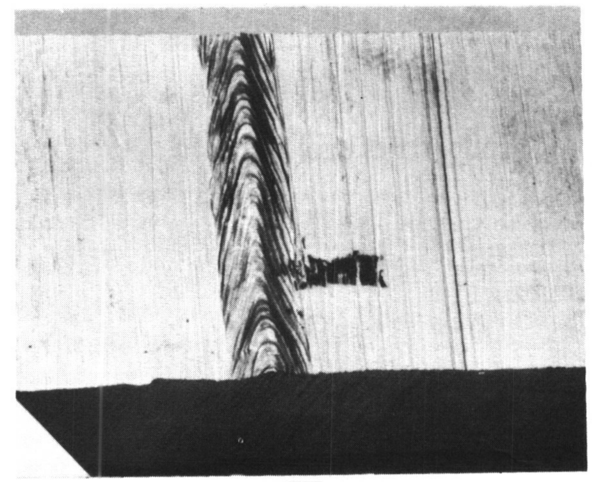
Tukon hardness measurements were made on selected specimens: (1) horizontally across the weld at mid-thicknesses, (2) vertically across the centerline of the weld, and (3) vertically across plate beyond the heat affected zone (HAZ).

Results

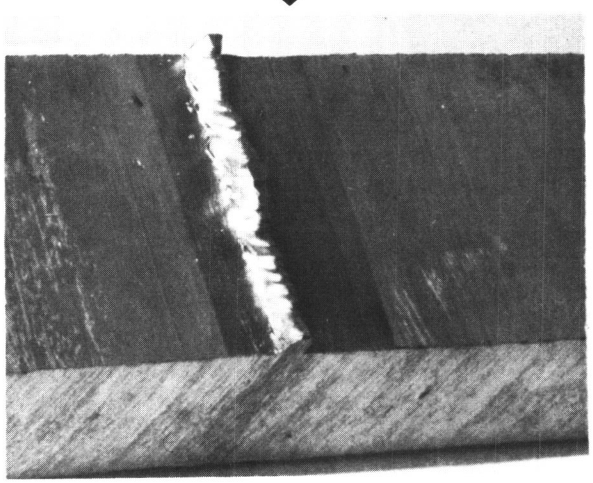
Welding speed and power input affect penetration, weld geometry, microstructure and strength of electron beam welds in 2219 plate as shown in Figures 1 and 2. Increasing the welding speed from 44 to 90 ipm increased strengths, even though an increase in power input from 6 to 9.2 KW was required to penetrate the 1/2-inch thick plate satisfactorily at the highest speed. Welding at 44 ipm made less efficient use of beam power as was apparent in (1) the excess penetration bead, (2) underfill and wider face bead, and (3) greater width of entire weld profile. It was found that approximately 13 KW per inch of thickness was adequate for penetrating 2219 at a speed of 60 ipm and for developing satisfactory strengths as shown in Table III. No difference in power requirement was noted for vertical vs. flat position welding.

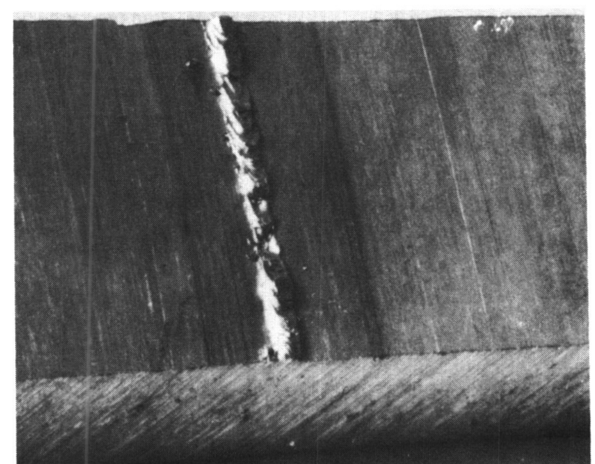
44 IPM, 300 MA, 20KV					90 IPM, 390 MA, 23.5KV			
TS KSI	YS KSI	EL.% 2-IN.	EFF. %		TS KSI	YS KSI	EL.% 2-IN.	EFF.%
49	36	9.0	75		54	38	8.0	82





FACE OF WELD
Ix





ROOT OF WELD
Ix

FIGURE 1. EFFECT OF WELDING SPEED AND POWER INPUT ON WELD GEOMETRY AND STRENGTH OF EB WELDED 2219-T81 1/2-IN. THICK PLATE.

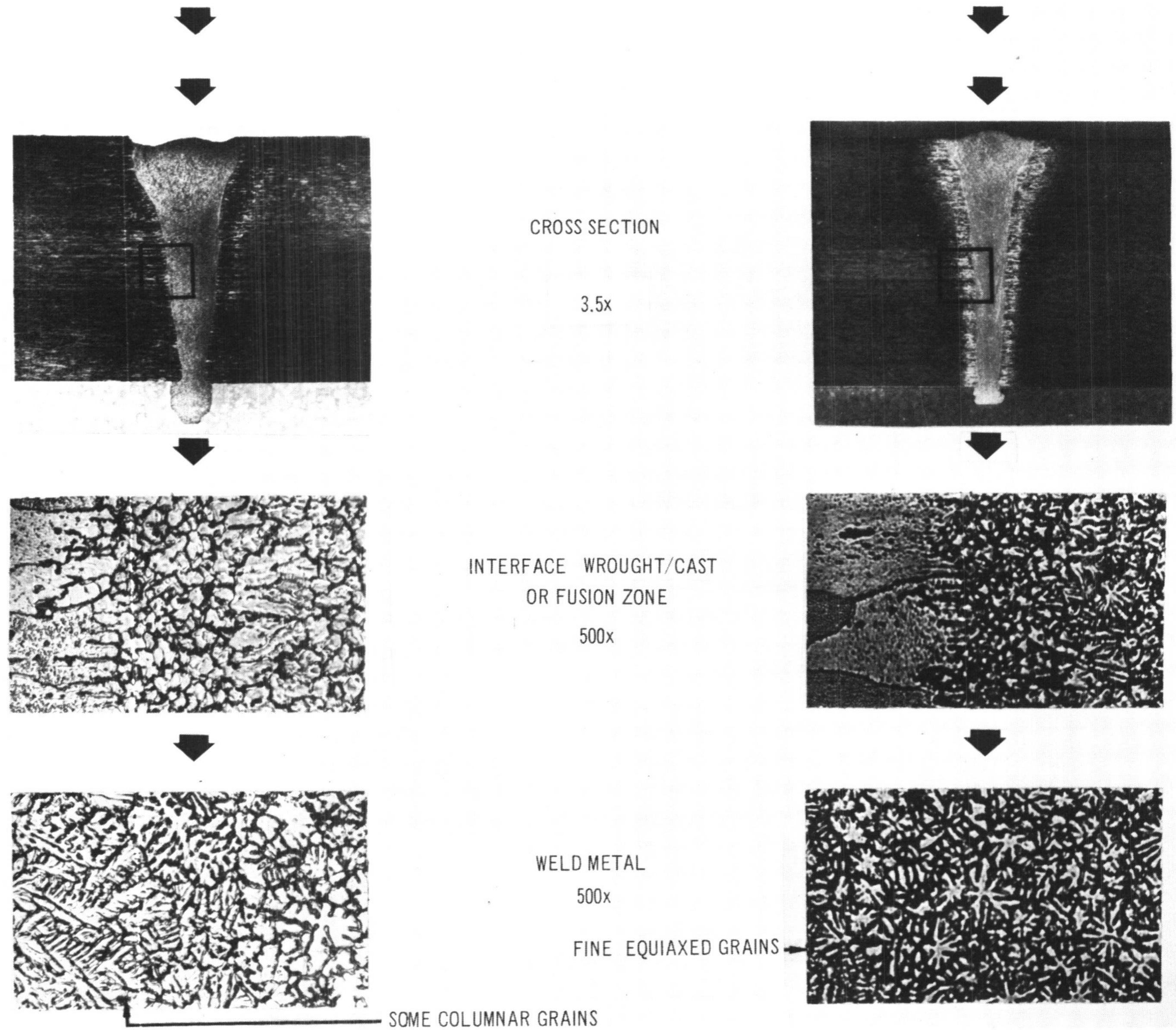


FIGURE 2. EFFECT OF WELDING SPEED AND POWER INPUT ON MACRO- AND MICRO- STRUCTURE OF EB WELDED 2219-T81 1/2-IN. THICK PLATE.

Weld Appearance and Soundness

Bead contours of the weld made at 90 ipm (Figure 1, right) are sufficiently smooth to be acceptable "as is" while the contours of the other weld (Figure 1, left) are too uneven to be satisfactory without employing some means to remove the excess metal and to fill in the low areas. The effectiveness of a defocused beam, smoothing pass on face and root beads is shown in Figures 3, 4, and 5 of EB welds in 2 3/8 inch and 1 1/4 inch thick plate. The dark band appearing on the plate surface adjacent to the welds results from vapor deposition within the shielding box in the vacuum chamber. The depression in the bead in the 2 3/8 inch plate about 2 inches from the start of the weld (Figures 4 and 5) is the remaining evidence that the gun arced momentarily in the fusion pass weld. The relatively smooth penetration or root bead on 1/2 inch thick plate shown in Figure 6 requires no smoothing pass. Typical cross sections of these welds are illustrated in Figure 7.

The need for a smoothing pass may be two-fold: (1) as noted above, to provide a more uniform surface contour of the beads by eliminating underfill, undercut, excess buildup on the face, and excess penetration of the root, and (2) to effect tie-in at the toes of the penetration beam where molten metal tends to roll over and not fuse with the base metal. This condition associated with the penetration bead is illustrated by photomicrographs, i.e., Figure 8a, lack of fusion extending up the sidewall of 1/2 inch thick plate, and Figure 8c, slight indication of lack of tie-in at the toe of 1 inch thick plate. The line extending up the sidewall in Figure 8a appears to be a remnant of oxide film from the plate surface. This and other enumerated conditions may be related in part to cleanliness, or lack of it, such as inadequate scraping of the metal surface to remove oxide film prior to welding.

Use of a backup plate is at least partially effective in controlling penetration bead contour to obtain a more uniformly even bead. Fractured tensile specimen from welds made employing a backup revealed some pore-like cavities at the root. The concave contour may result from the hole drilled by the jet-vaporized metal being either (1) not completely pushed through the thickness of the plate or (2) trapped against the surface of the backup plate. A slightly concave contour is not deterimental to strengths; however, an appreciable amount of entrapped "porosity" can seriously lower tensile strength, (See Table VIII, Specimen No. 6A2), especially in relatively thin gage plate or sheet.

Radiographic examination of EB welded panels has shown X-ray quality of many panels to be Class II or better (ABMA Spec. PD-R-27A). Likewise, examination of the radiographs made parallel to the weld generally reveal Class II or better. Porosity may be distributed throughout the weld from face to root or somewhat localized in the region toward the root of the weld.

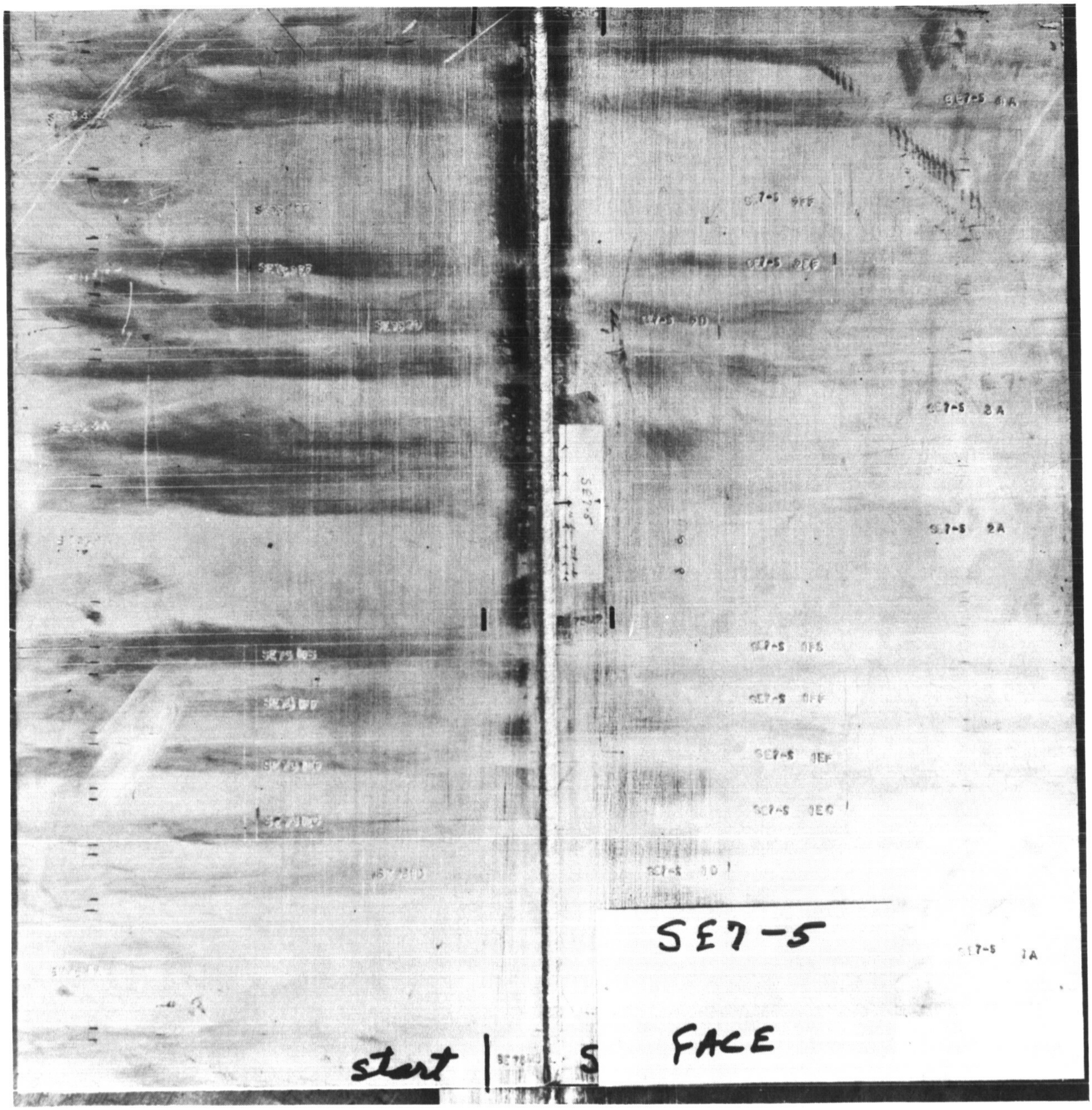
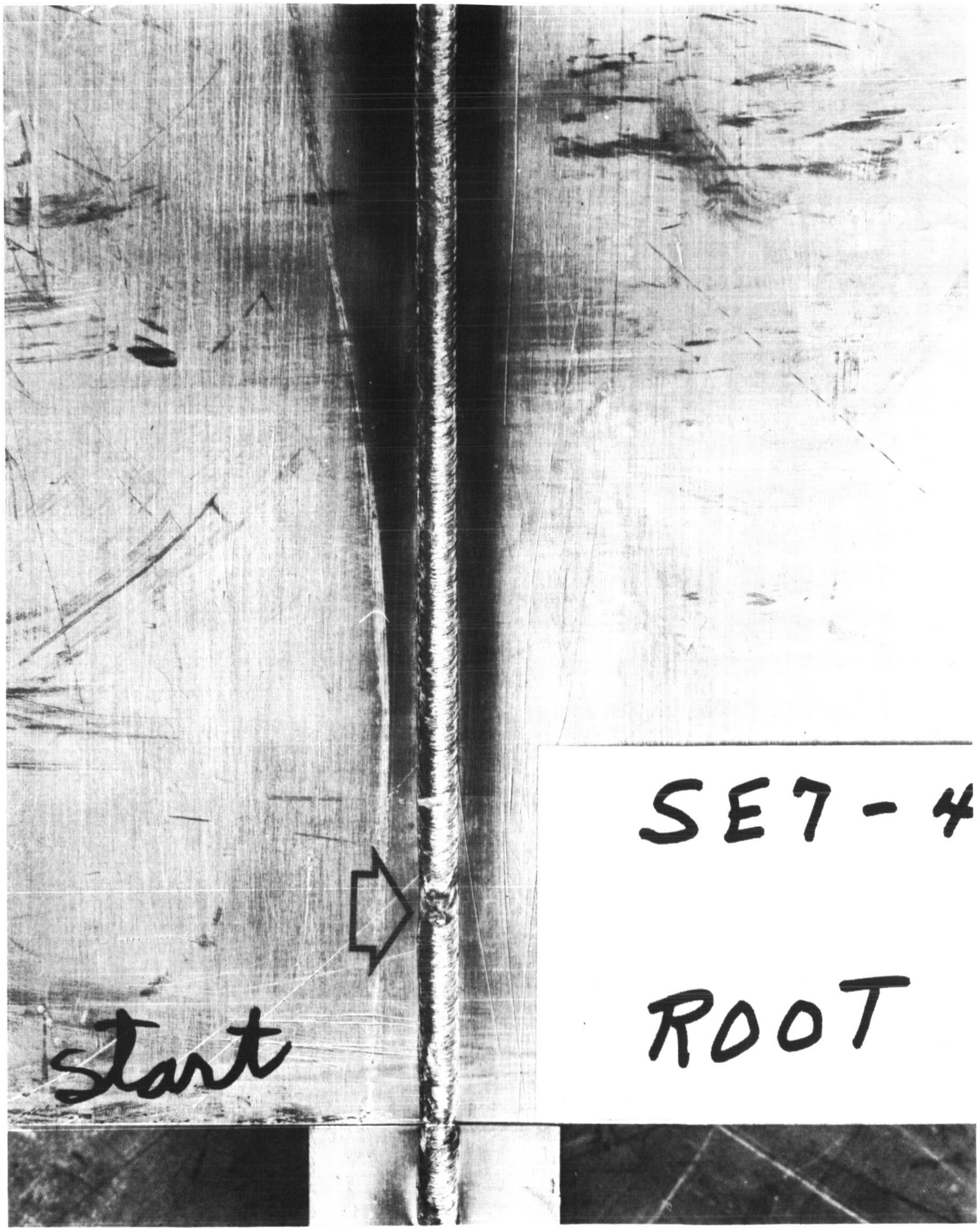


FIGURE 3. EB WELDED 1-1/4-IN. THICK PLATE, FACE SIDE, FULL VIEW, MARKED FOR SECTIONING AS CUT TO 18x20-IN. (WELDED 36x20-IN.).

NOTE: NOTE RUN-ON TAB, THE 4-IN. WIDE DARK BAND CENTERED ON THE WELD IS THE RESULT OF VAPOR DEPOSITION WITHIN THE SHIELDING BOX IN THE CHAMBER. THE INNER DARK BAND IS THE VAPOR DEPOSIT FROM THE SMOOTHING PASS. ARROW LOCATES DEPRESSION IN BEAD.

FIGURE 4. EB WELDED 2-3/8-IN. THICK, FACE SIDE WITH SMOOTHING PASS, CLOSE UP OF START END.



NOTE: DEPRESSION IN SMOOTHING BEAD AT ARROW ABOUT 2-IN. FROM START.

FIGURE 5. EB WELD 2-3/8-IN. THICK PLATE, ROOT SIDE WITH SMOOTHING PASS, CLOSE UP OF START END.

FIGURE 6. EB WELDED 1/2-IN. THICK PLATE, ROOT SIDE, NO SMOOTHING PASS, CLOSE UP OF START END.

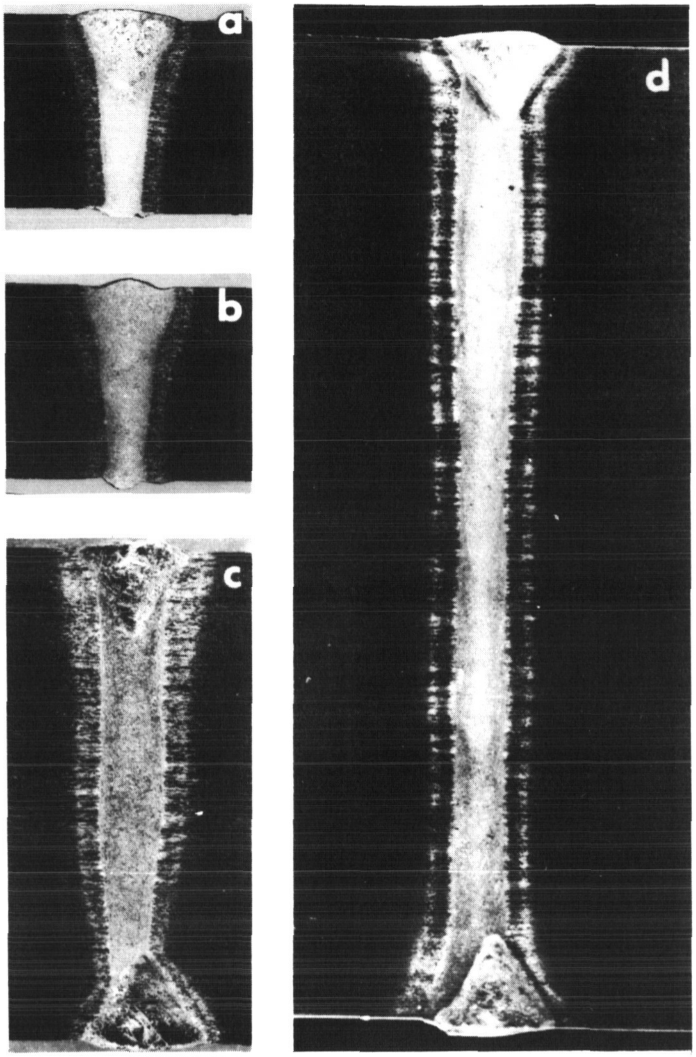


FIGURE 7. CROSS SECTION (2x) OF EB WELDS IN 1/2-IN. (a) AND (b), 1-1/4-IN; (c), AND 2-3/8-IN; (d), THICK 2219 PLATE WITH ANGULAR SMOOTHING PASSES (a, c, AND d) AND WITHOUT A SMOOTHING PASS (b).

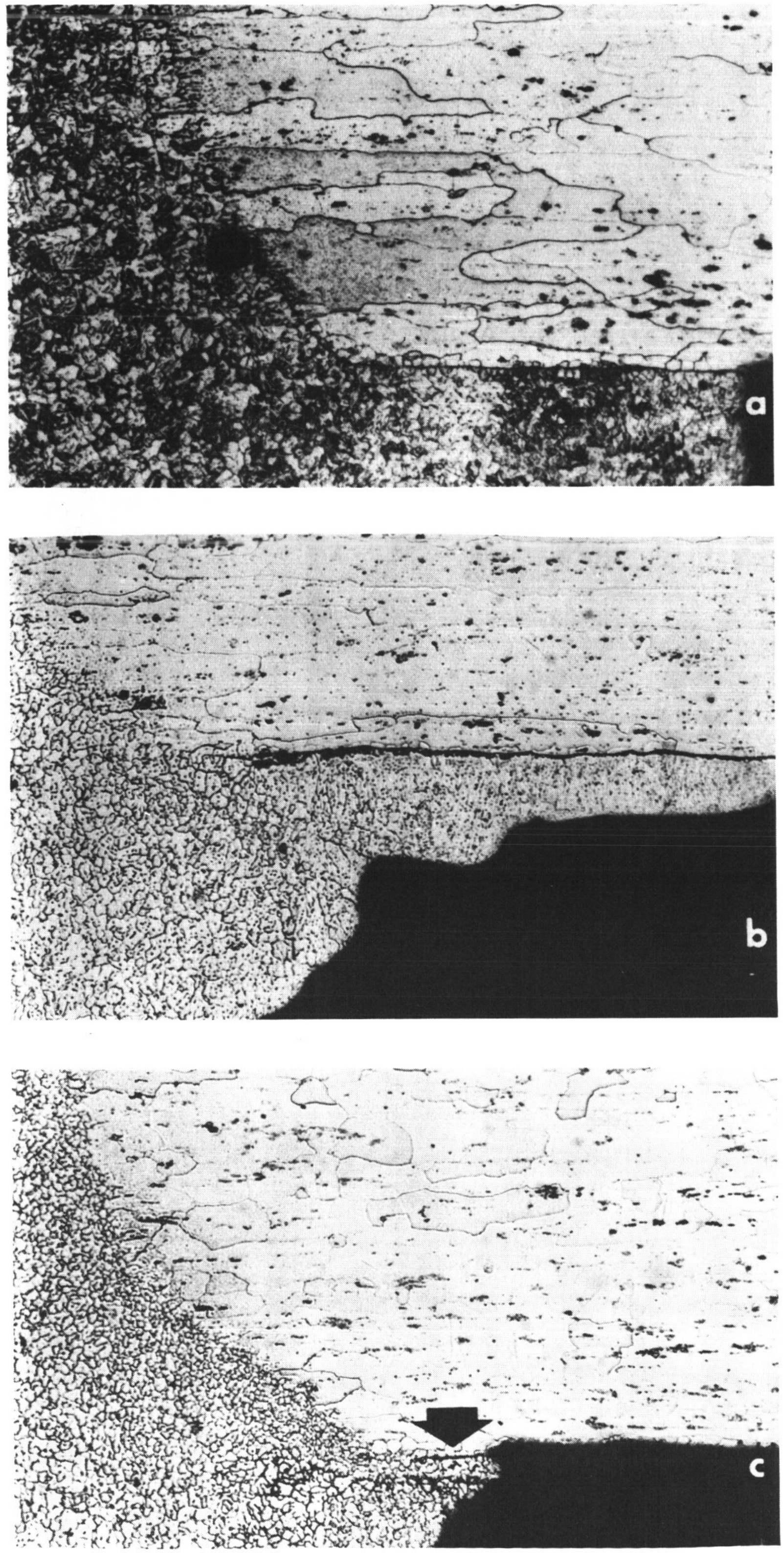


FIGURE 8. PHOTOMICROGRAPHS (200x) AT TOE OF EB WELD IN 1/2-IN. (a), 3/4-IN. (b), AND 1-IN. (c) PLATE (TOP TO BOTTOM) SHOW CONDITIONS ON ROOT SIDE WITH NO SMOOTHING PASS.

There is some indication of decreasing soundness with increasing gage.

Mismatch in EB welded panels has not been much of a problem. In heavy gage plate, mismatch of up to 0.080 inch was encountered and welded without difficulty as illustrated by the cross section of 2 3/8 inch plate shown in Figure 7d. Both the initial fusion pass and the smoothing pass were satisfactory without any compensating adjustments.

Misalignment can be very critical in EB welding due to the narrow beam usually employed for the fusion pass. Similarly, a gap between abutting edges can be a problem. The narrower the weld, obviously the more problem with alignment or fitup. Some compensation can be effected in a smoothing pass where the beam can be defocused a fairly wide weld and/or controlled to obtain a given depth of penetration.

Distortion has been encountered and can be a problem in EB welding. Considerable shrinkage distortion was observed in the 1/2 inch thick panels. The distortion appeared to be related to the contour of the fusion pass weld and to be accentuated by a smoothing pass --- the more angular or divergent the sides of the weld, the greater the distortion. The desirability of parallel-sided welds to equalize shrinkage and minimize distortion is readily apparent.

Tensile Properties vs. Type Specimen

Strengths of EB welded 2219 aluminum alloy plate vary with welding conditions and with type specimen employed as shown in Tables IV, V, and VI. Joint strengths increase with increasing specimen width for all four thicknesses of base plate from 1/2 through 2 3/8 inches (Table V) and were greater for full thickness slices with smoothing pass on face and root than for round specimens machined from the joint. The full thickness slice specimen, beads intact, demonstrates the importance of bead contour in structural application. Cross sections of the full thickness specimens (Figure 9) reveal the rounded contour of the smoothing passes and the nearly parallel sided profile of the fusion pass. (Note by contrast the angular contour of the smoothing pass on the welds shown in Figure 7.)

The two sets of so called "yield strength" values for 3/4 inch thick plate (Table V) reflect difference in welding conditions for different panels. The higher yield strengths are associated with higher welding speed (60 vs. 43 ipm) and accompanying lower energy input, i.e. 14.67 vs. 18.30 kilojoules per in./in. This improvement in mechanical properties is more apparent in the wider specimens.

Increasing specimen width to 1 1/2 inches or 2 1/2 inches in the gage length was accompanied by a significant increase in weld tensile and yield strengths for the 1 1/4 inch and 2 3/8 inch thick plate (Table VI). Full section specimens produced tensile strengths (TS) 5 to 10 ksi higher and yield strengths (YS) 10 to 20 ksi higher than the round specimen or the 1/2 inch thick flat (layer) specimens from

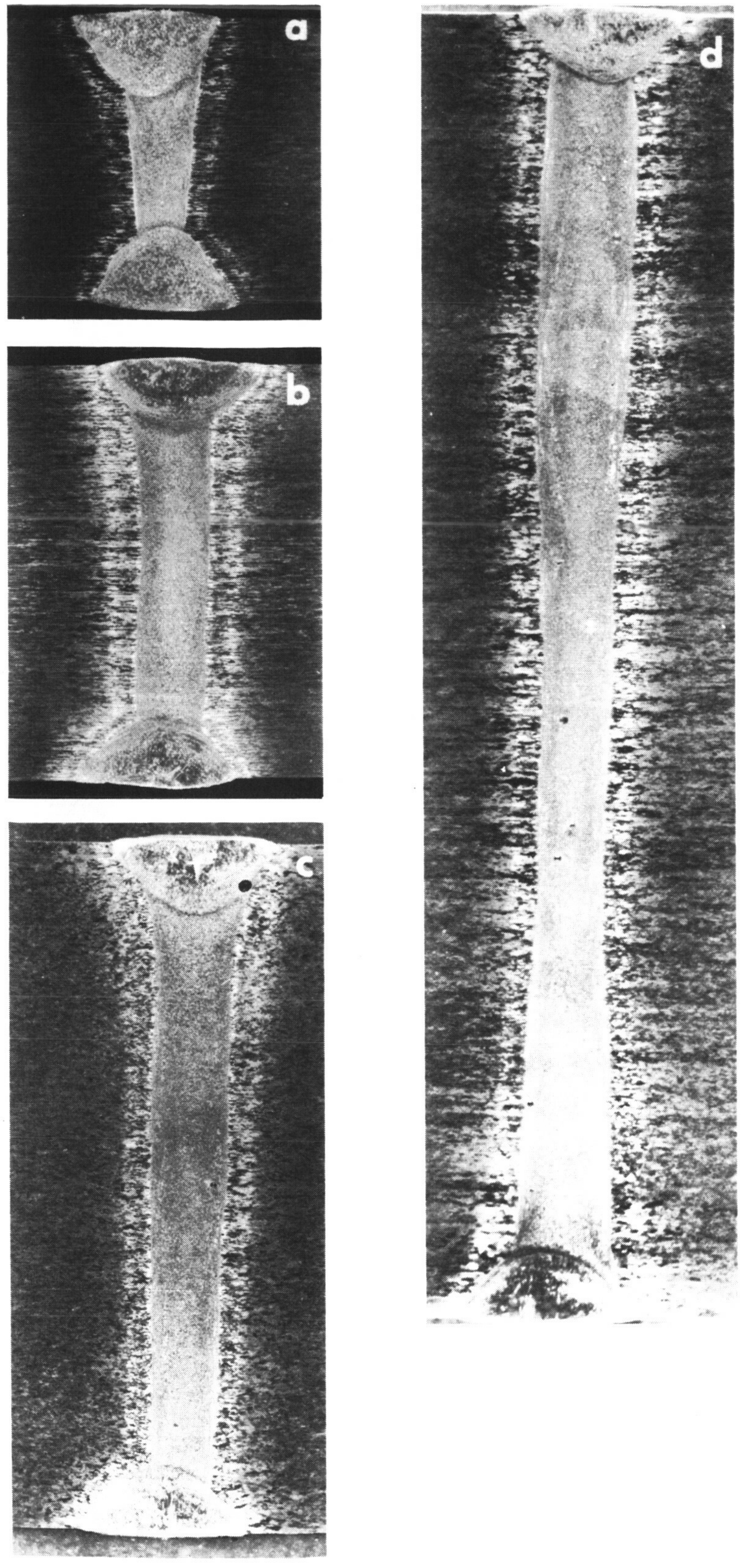


FIGURE 9. CROSS SECTION (3x) OF EB WELDS IN 1/2-IN. (a), 3/4-IN. (b), 1-1/4-IN. (c), AND 2-3/8-IN. (d) THICK 2219 PLATE WITH ROUNDED SMOOTHING PASSES FACE AND ROOT.

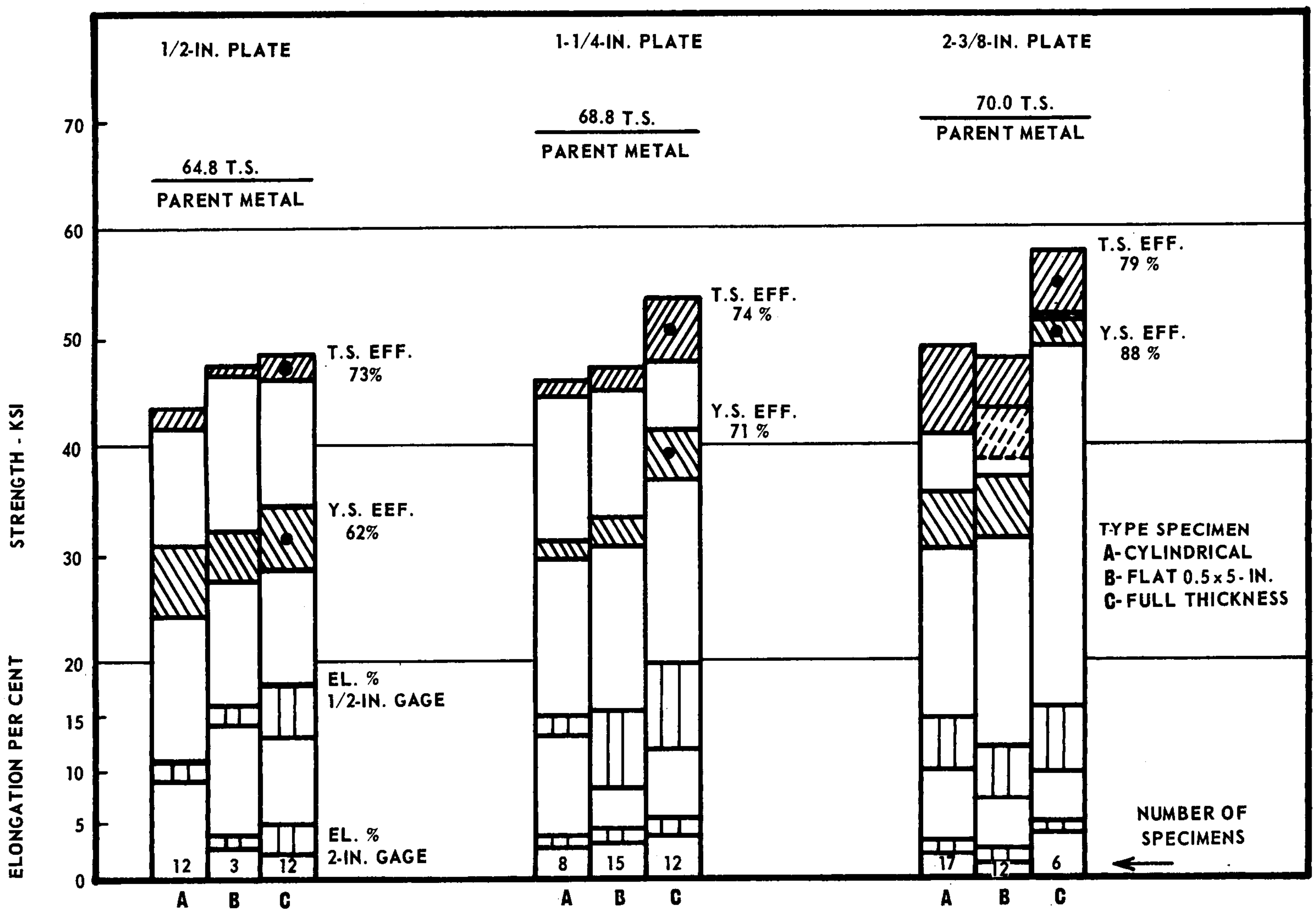
various locations across the thickness of the plate. Data are plotted as a bar graph in Figure 10.

Variation in strength of plate with location in the cross section is expected for heavy gage aluminum alloy material. Strength of the 2 3/8-inch thick 2219-T87 plate used in this EB welding investigation varied up to 5 ksi across the thickness --- higher strengths being developed on the surface and lower strengths in the center portion as shown in Table VII. However, strengths of the welds from these locations did not follow this same pattern and furthermore were influenced by weld quality. Discontinuities or defects were more apt to occur in the lower portion or root side of the EB welds. Thus these defects when located in the small "layer" specimen exerted an exaggerated effect on strength as compared to their presence in full thickness specimens. Tensile strengths of layer specimens were lowered disproportionately --- up to 9 ksi as shown in Table VII. As with MIG and TIG welds, mechanical type defects, i.e., non-fusion, porosity or voids, affect tensile strength but have little if any effect on yield strength, while heat effects are more readily apparent in changes in yield strength.

Tensile Properties vs. Plate Gage

Strengths of EB welds in these tests generally increased with plate gage for the constant thickness plate and for the variable thickness plate. Tensile strengths of 47, 51, and 55 ksi were developed by full thickness tensile specimens from equal-width welds in 2219-T87 plate 1/2-inch, 1 1/4-inches, and 2 3/8-inches thick, respectively. The values represent joint efficiencies of 73, 74, and 79 per cent of the parent metal employed (Table VI, Figure 10). Note that strengths given here for welds in thinner gages are not maximum obtainable by EB welding. Variable thickness specimens, originating from the Y-contour per sketch shown in Figure 11, developed strengths increasing up to about 54 ksi. This value was obtained for the 1 1/2-inch nominal thickness specimen in the stem of the Y. Data are given in Table VIII and plotted in Figure 12.

Strengths developed by welds in the thinner gages have been appreciably lower than those for heavier gages primarily due to the welding conditions being controlled to produce equal-width welds for the various gages. Thus, weld depth-to-width ratio was less favorable for thinner material. Maximum strengths obtained to date for welds in 1/2-inch thick plate are those given previously in Figure 1 and Table III --- TS 54 ksi and YS 38 ksi. Note this TS is comparable to that developed in the 2 3/8-inch gage while the YS is more than 10 ksi lower, being more nearly equivalent to the YS developed in the 1 1/4-inch gage plate. It may be that greater efficiency will continue to be realized in the heavier gages where a high weld depth-to-width ratio can be attained more readily along with a parallel sided weld contour. Furthermore, the smoothing pass,



NOTES:

1. STRENGTHS FOR THINNER GAGES ARE NOT MAXIMUM OBTAINABLE BY ELECTRON BEAM WELDING.
2. APPROXIMATLY CONSTANT WIDTH WELDS FOR VARIOUS GAGES.

FIGURE 10. BAR GRAPH OF TENSILE PROPERTIES OF EB WELDED 2219 PLATE 1/2 TO 2-3/8-IN. THICK - VARIOUS TYPE SPECIMENS.

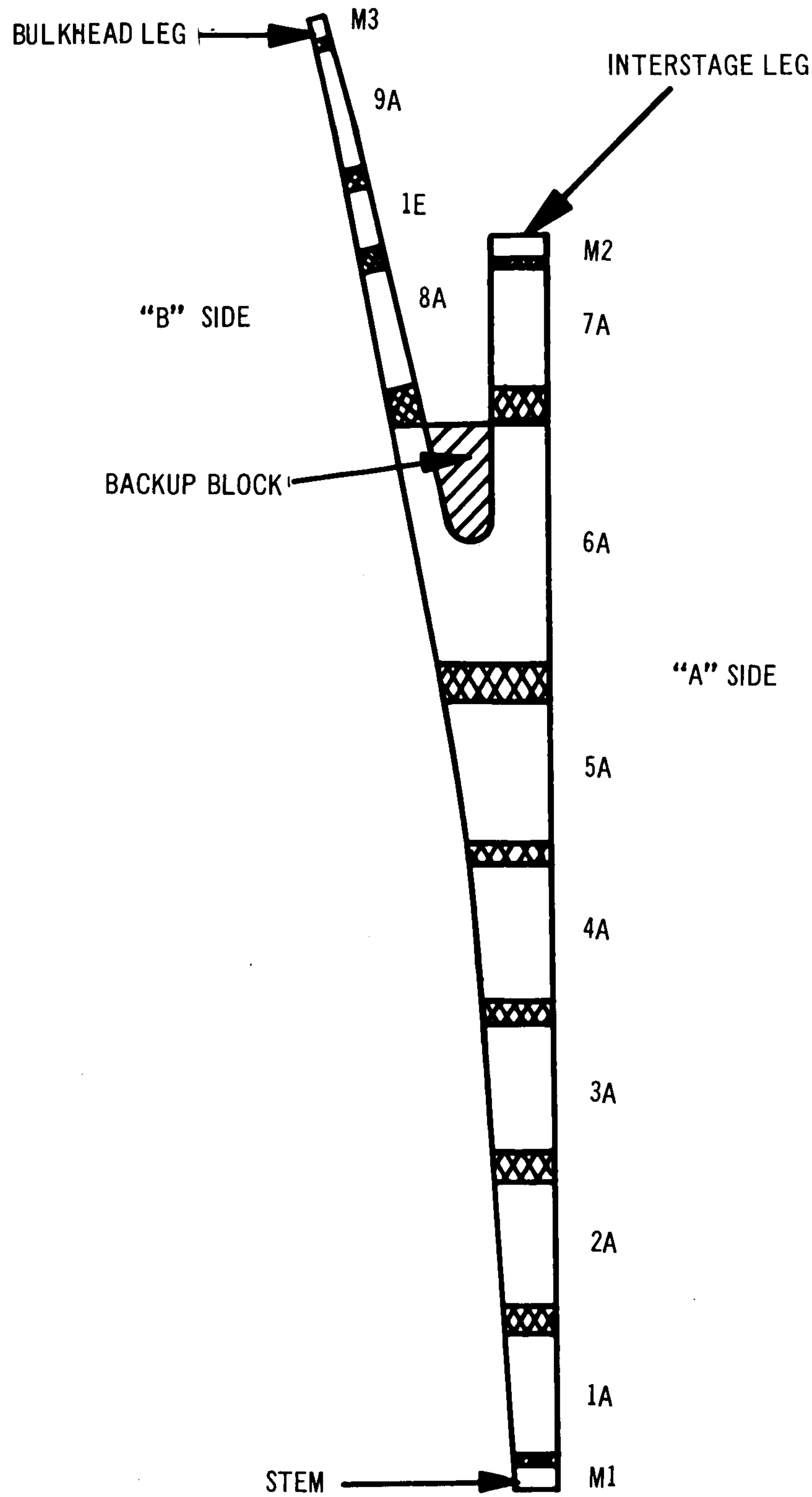
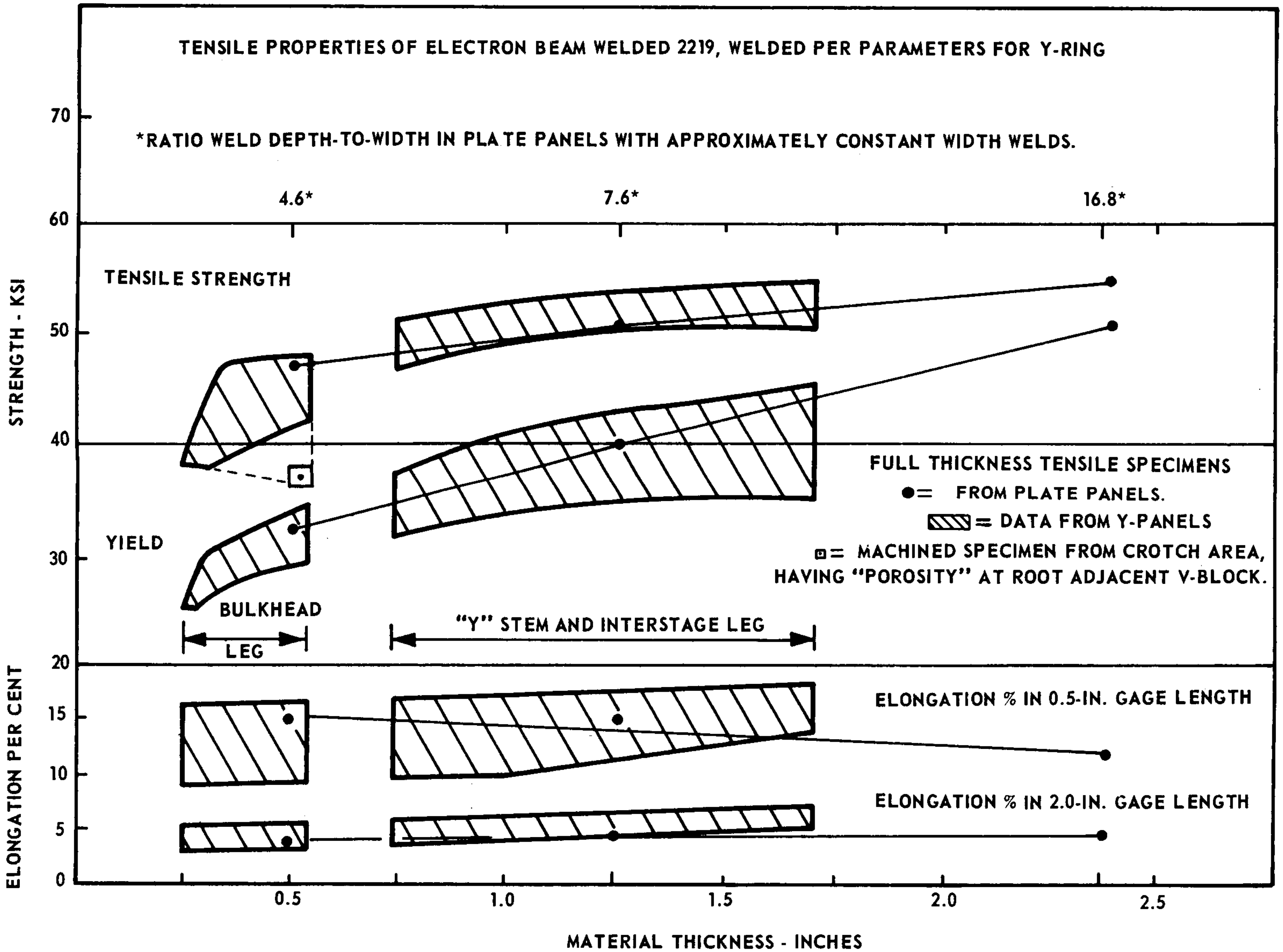


FIGURE 11. SKETCH OF Y-SHAPED CONFIGURATION SHOWING LOCATION OF TENSILE SPECIMENS IN CROSS SECTION OF WELDED JOINT.



NOTE:
STRENGTHS FOR THINNER GAGES ARE NOT MAXIMUM OBTAINABLE BY E B WELDING.

FIGURE 12. CURVE OF TENSILE PROPERTIES vs. MATERIAL THICKNESS FOR EB WELDED PLATE AND Y-SHAPE.

or rather the heat associated with the smoothing pass, may have a more detrimental effect in the thinner gages. For instance, welded 1/2-inch plate (no smoothing pass, Figure 7b) developed a YS of 35 ksi while the companion samples with a smoothing pass (Figure 7a) developed only 30 ksi YS. This situation reverts to the fundamental idea of effective use of energy input in welding. Excess energy that is converted to heat and absorbed by the base metal is detrimental to joint strength in EB welding as in MIG, TIG, etc. The excessively low yield strengths (27 and 26 ksi) developed by the 0.34-inch and 0.31-inch thick samples noted in Table VIII are evidence of the overheating experienced by the metal during an inadvertently slow smoothing pass. In this case, the overheating was sufficient to lower even the tensile strength of one specimen to 38 ksi.

Tensile Properties of Y-Ring

Tensile properties developed in the Y-Ring were comparable to those obtained from the Y-panels as shown in Table IX. Again, it is noted that strengths in the Y-Ring bulkhead leg (less than 1/2-inch in thickness) are low --- degraded to a range approaching those normally obtained with the MIG or TIG welding process.

Ductility

EB welds with their generally very narrow HAZ develop good ductility locally --- over a very small distance centered on the weld. Good elongation is exhibited by cast metal and wrought metal within about 1/2 inch of the weld centerline, i.e., 7 to 11 per cent El. in a 1-inch gage length across the weld measured on full thickness tensile specimens. Reduction in area of cylindrical specimen averaged about 25 per cent and ranged from 16 to 32 per cent. Data are presented in Table X. Visual examination of tensile fractures gives evidence of considerable "tenacity" at the weld interface and definitely little evidence of brittle fractures.

Guided bend tests of these EB welds in 2219-T87, as expected, contribute very little significant information regarding weld ductility. Although the load to failure was relatively high, the bend angle obtained was quite limited and the elongation measured on the tension side in various increments was less than that measured on tensile specimens. Bend angle should be expected to be limited due to the very limited expanse of ductile material that has the ability to deform, i.e., the weld metal and the HAZ. Since both of these are narrow and the high strength parent material itself has limited ductility, little overall bending is accomplished even with sound, locally ductile welds. The point to note is that bend angle does not appear to be limited by lack of ductility in the EB weld or weld interface but rather by the narrow width of the ductile areas. The ductility of a welded joint in an aluminum alloy depends on the characteristics of (1) the cast weld metal, (2) of the parent metal, and (3) of the HAZ. A wide HAZ could most likely provide good bend ductility considering that the heat of welding has effected a partial anneal of the parent metal for a considerable distance from the weld interface. Conversely, a very narrow weld having a very narrow HAZ might be expected to possess a more limited ability to deform, considering that there has been little resolution or annealing of the parent metal.

Hardness

Tukon hardness traverse of several EB welds in 2219-T81 and -T87 indicated that the width of the HAZ on either side of the weld was about equivalent to the width of the weld itself. Thus with a weld 1/4-inch wide, the total width across weld and HAZ would be 3/4 inch. Hardness change starts quite abruptly at the weld interface. Roughly, values of 75 to 80 were measured in the weld, 80 to 125 in the HAZ and 125 to 140 in the unaffected -T81 parent material.

Metallographic Examination

A photomacrograph of an EB weld in 2 3/8-inch thick 2219-T81 plate, shown in Figure 13a at a magnification of 4X, illustrates slight variations in weld width across the thickness of the plate. The configuration suggests a tendency for refocusing, within the plate, of the energy transmitted by the electron beam. Note the narrowing of the weld at about 2/3 the distance through the thickness and then the divergence again toward the root. A difference in structure was observed in the re-solidified weld metal along the interface from surface to surface as evidenced in Figures 13b through 13g at 50X. A band of very fine structure occurs immediately adjacent the relatively undisturbed parent metal. This band is very narrow in some areas (b, c, and f), broadens out considerably in others (d and e), and dominates the periphery of the smoothing pass (13g). Columnar grains are evident just inside the fine structure in areas near the face and root surfaces of the weld, as shown in the lower part of 13b and top part of 13f. (Columnar grains had been observed previously in a weld in 1/2-inch plate welded at 44 ipm as shown in Figure 2).

Indication of the very high thermal gradient occuring in these EB welds is shown by the microstructure at the interface at higher magnifications, 200X, in Figure 14c and 14d. Note (1) little or no grain boundary melting and (2) evidence of partial melting and re-solidification within part of a grain (14 b and d) without even disturbing the grain boundary in many cases. The grain size of this lot of -T81 material is considerably larger than that of the lot of -T87 material shown in Figure 14a and c and used in later tests.

Comparison of TIG vs. EB weld cross section is shown in Figure 15 for 3/4-inch 2219-T87. The TIG weld nugget (a, 2.5X) measures about 3 to 4 times wider than the EB weld (b, 2.5X) across the thickness of the plate and about twice as wide on the face of the weld with its smoothing pass. The sharply defined interface of the EB weld (d, 200X) contrasts strongly with the broader, diffused interface of the TIG weld (c, 200X).

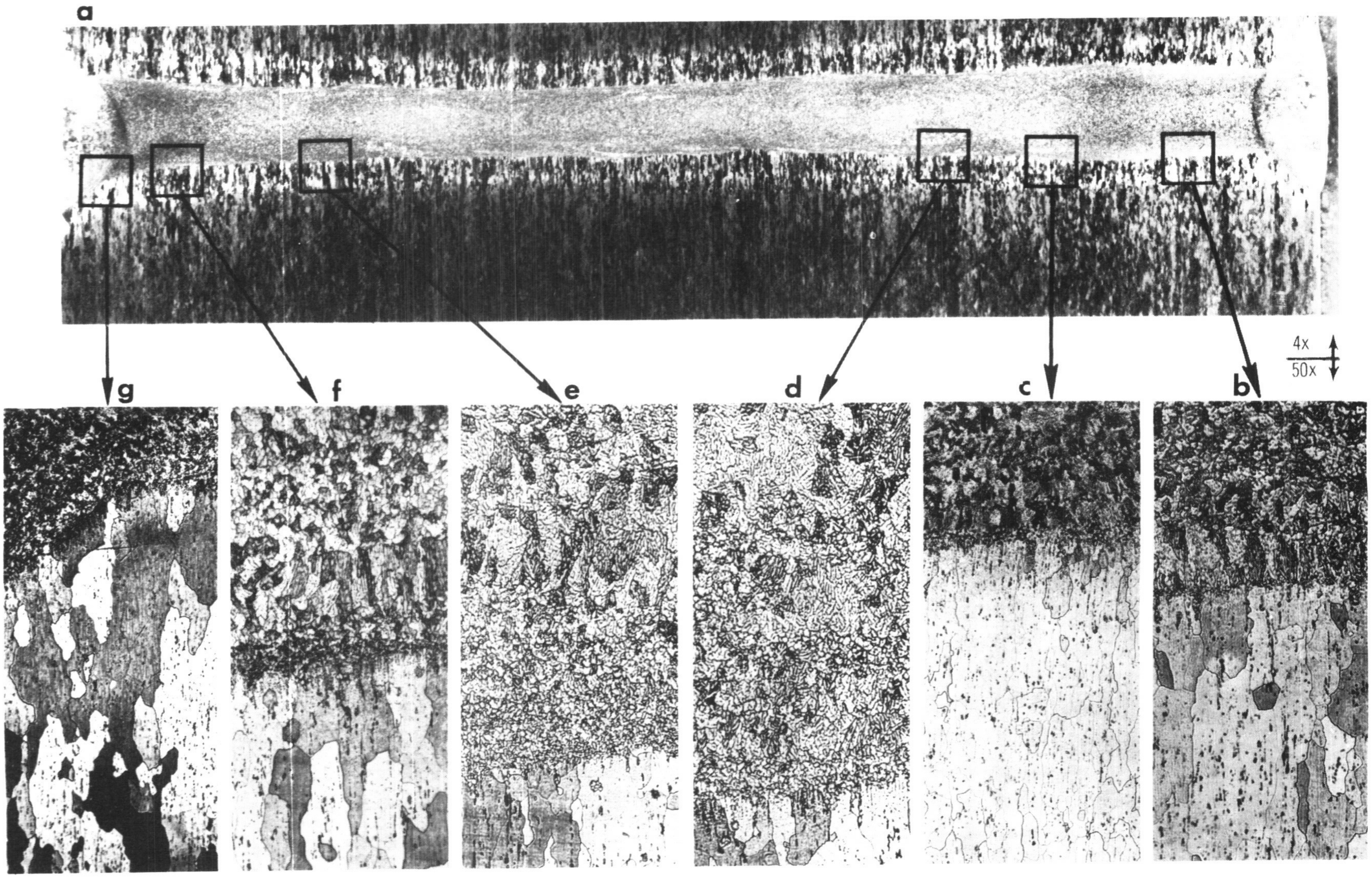


FIGURE 13. CROSS SECTION OF EB WELD IN 2-3/8-IN. 2219-T81 PLATE (a) AND PHOTOMICROGRAPHS OF INTERFACE AREAS (b THRU g).

2219-T87

2219-T81

(NOTE PARTIALLY MELTED GRAINS WITH BOUNDARIES ESSENTIALLY INTACT WITHIN THE BLOCKED AREAS)

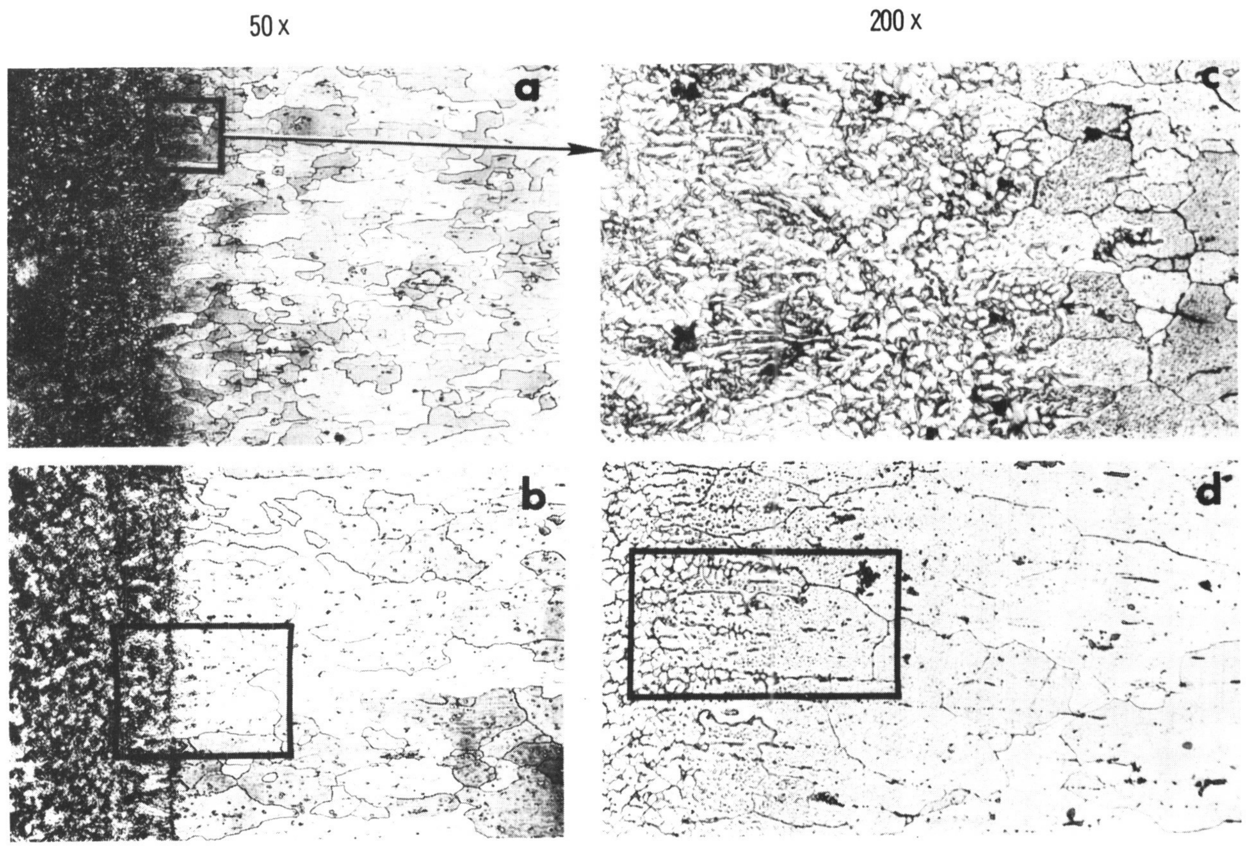
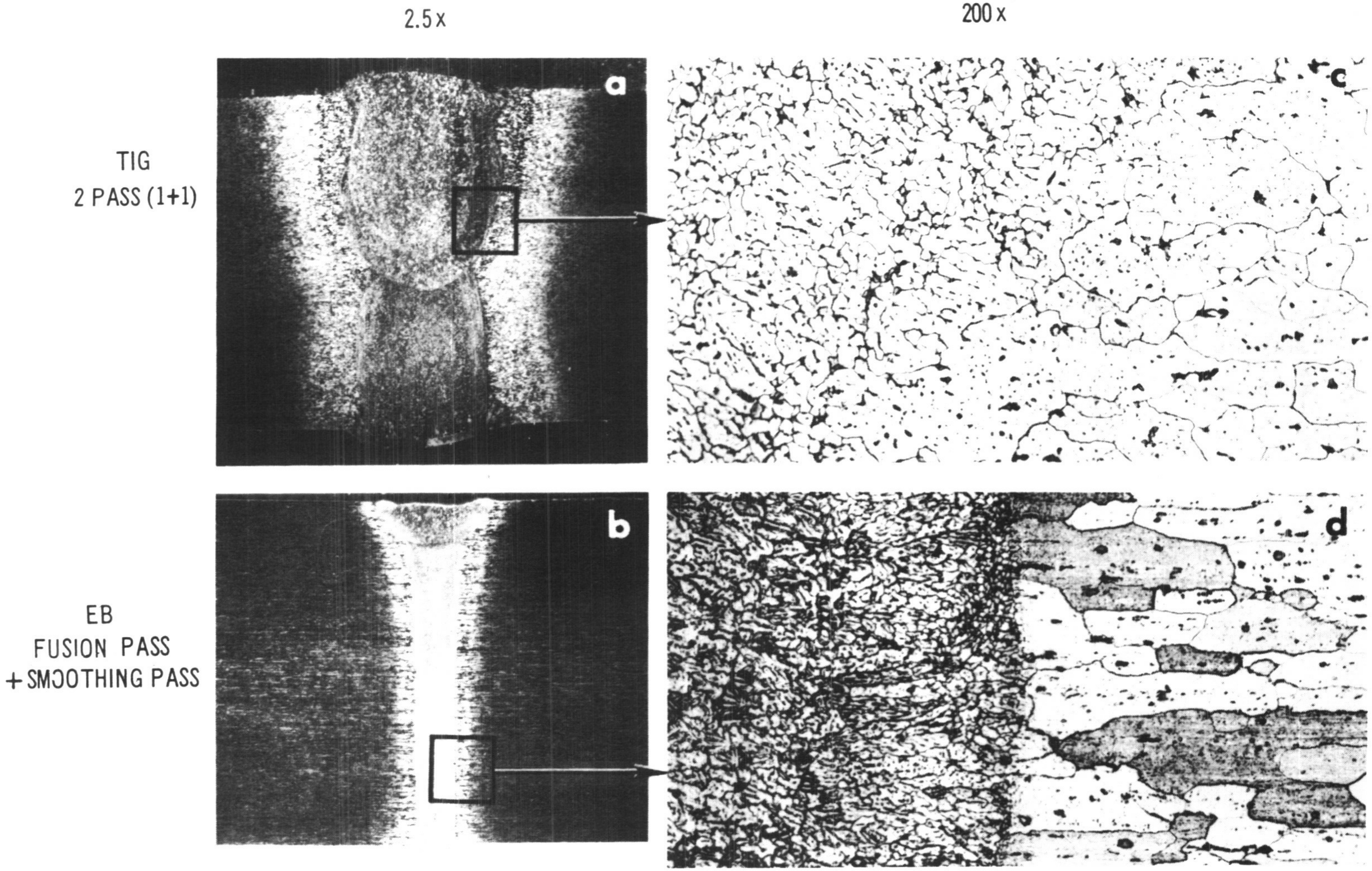


FIGURE 14. PHOTOMICROGRAPHS OF INTERFACE AREAS IN EB WELDED 2-3/8-IN. THICK 2219-T87 AND T81 PLATE SHOWING DIFFERENCE IN GRAIN SIZE AND SOME PARTIALLY MELTED GRAINS.



NOTE: PHOTOMICROGRAPHS ON RIGHT, SHOW FAIRLY WIDE CAST/WROUGHT INTERFACE FOR TIG WELD (c) TOP AND SHARPLY DEFINED INTERFACE FOR EB WELD (d) BOTTOM.

FIGURE 15. TIG vs. EB WELDED 3/4-IN. 2219-T87 PLATE.

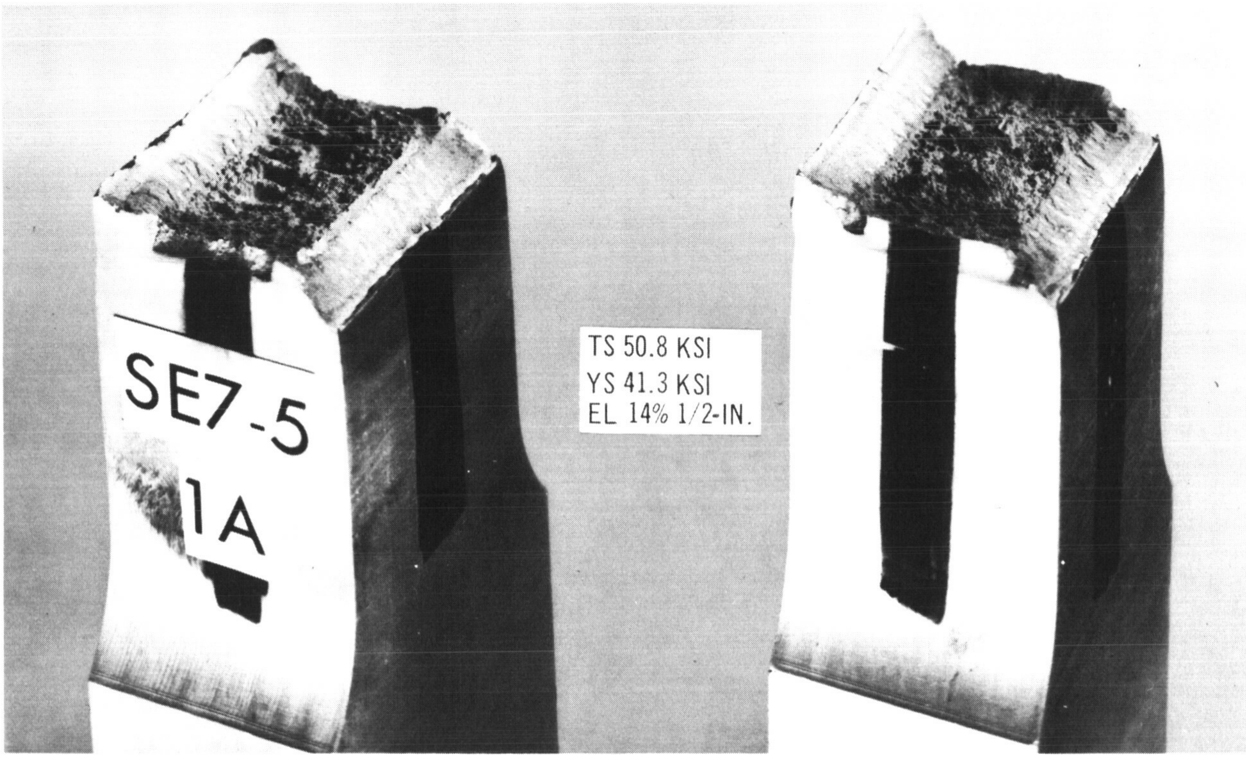
Tensile Properties vs. "Defects"

Intentionally included in our early tests were some specimens containing considerable porosity in order to determine the effect of porosity on strength. Weld samples of 2 3/8-inch plate, X-ray Class 2 and 3, developed TS of 48.1 and 47.6 ksi (in 1/2-inch wide slice specimens) while samples of Class 5 X-ray rating developed 45.7 ksi. Thus, it is evident that porosity can be detrimental in EB welds. However, porosity has not shown as deleterious an effect on strength as was anticipated. Considering the narrow width of the weld or cast metal and the apparent large cross sectional area occupied by porosity in several samples, the strengths of these were surprisingly high.

Photographs of fractured full section tensile specimens in 1 1/4-inch and 2 3/8-inch plate are shown in Figures 16 and 17. The 1 1/4-inch specimens contained small scattered porosity while the 2 3/8-inch specimens also contained some areas of moderate to "gross porosity". The path of the fracture followed the interface fairly closely with some pores visible on the surfaces. Strengths developed by the 1 1/4-inch specimen apparently were little affected by the porosity. Close-up views of the fractures in 2 3/8-inch samples shown in Figures 18 and 19 reveal some porosity and several "flat" spots on the fracture. These conditions had little if any effect on tensile strength. However, the presence of a third condition illustrated in Figures 20 and 21 is associated with appreciably lower strengths --- from 56 to 58 ksi down to 52 ksi tensile strength. The detrimental condition appears to be a non-fused spot and occurs generally on a "flat" spot. (Non-fused spots are marked by solid black arrows in Figures 20 and 21.) Porosity and non-fused areas generally were located principally near the center of the thickness or toward the root of the weld.

The specimen shown in Figure 20 originated from the panel shown in Figures 4 and 5. Open arrows mark the location of the surface depression in both photos. It is evident from the fracture that the arc disturbance (momentary interruption or near arc-out) causing the depression had created, or been accompanied by, considerable turbulence in the weld. In addition to the porosity in the bottom third of the weld, several voids and a "flat" spot are located immediately in line with the depression, and adjacent to this is located a flat spot with a non-fused spot. With all these "defects", a TS of 52 ksi was developed.

The non-fused spots in the second specimen (Figure 21) are located at the root of the weld just above the smoothing pass. The porosity and voids in this specimen are plainly located just above the center of the specimen. Again, a TS of 52 ksi was developed --- being only 6 ksi lower than the maximum of 58 ksi.



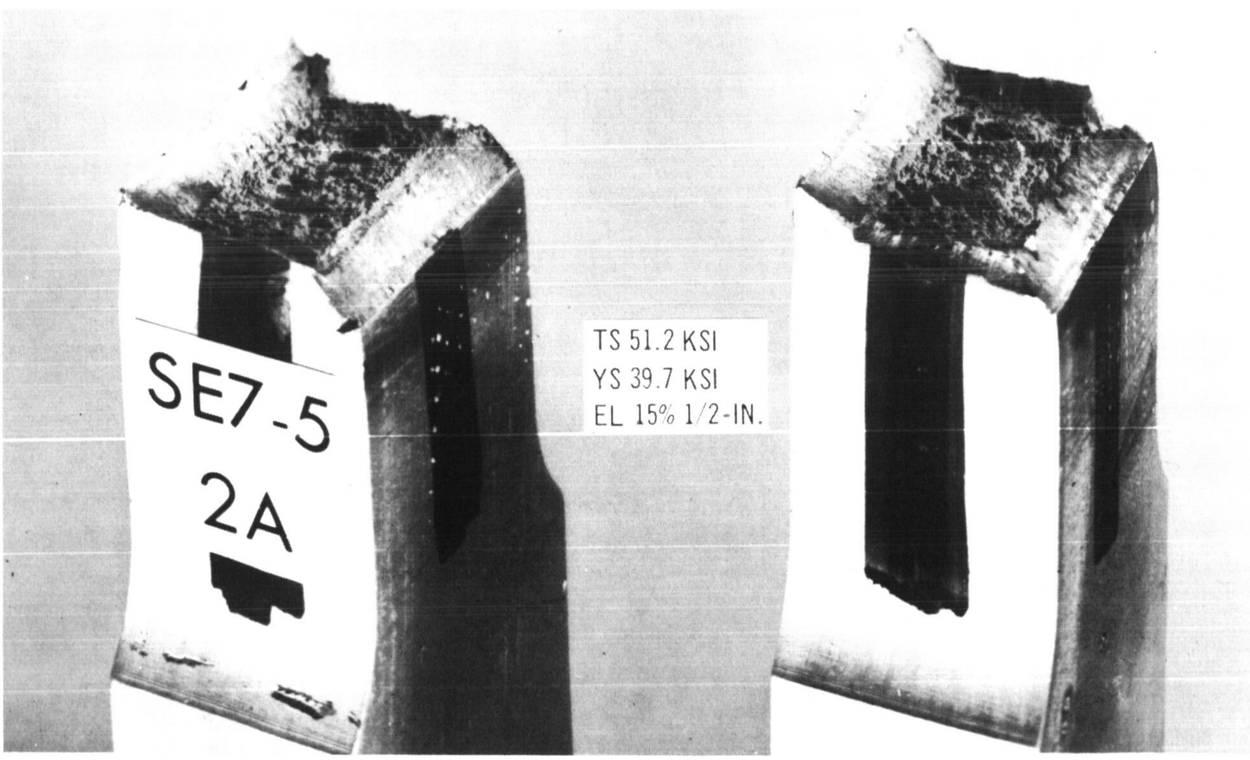


FIGURE 16. FRACTURED FULL THICKNESS TENSILE SPECIMEN IN 1-1/4-IN. THICK EB WELDED 2219 PLATE.

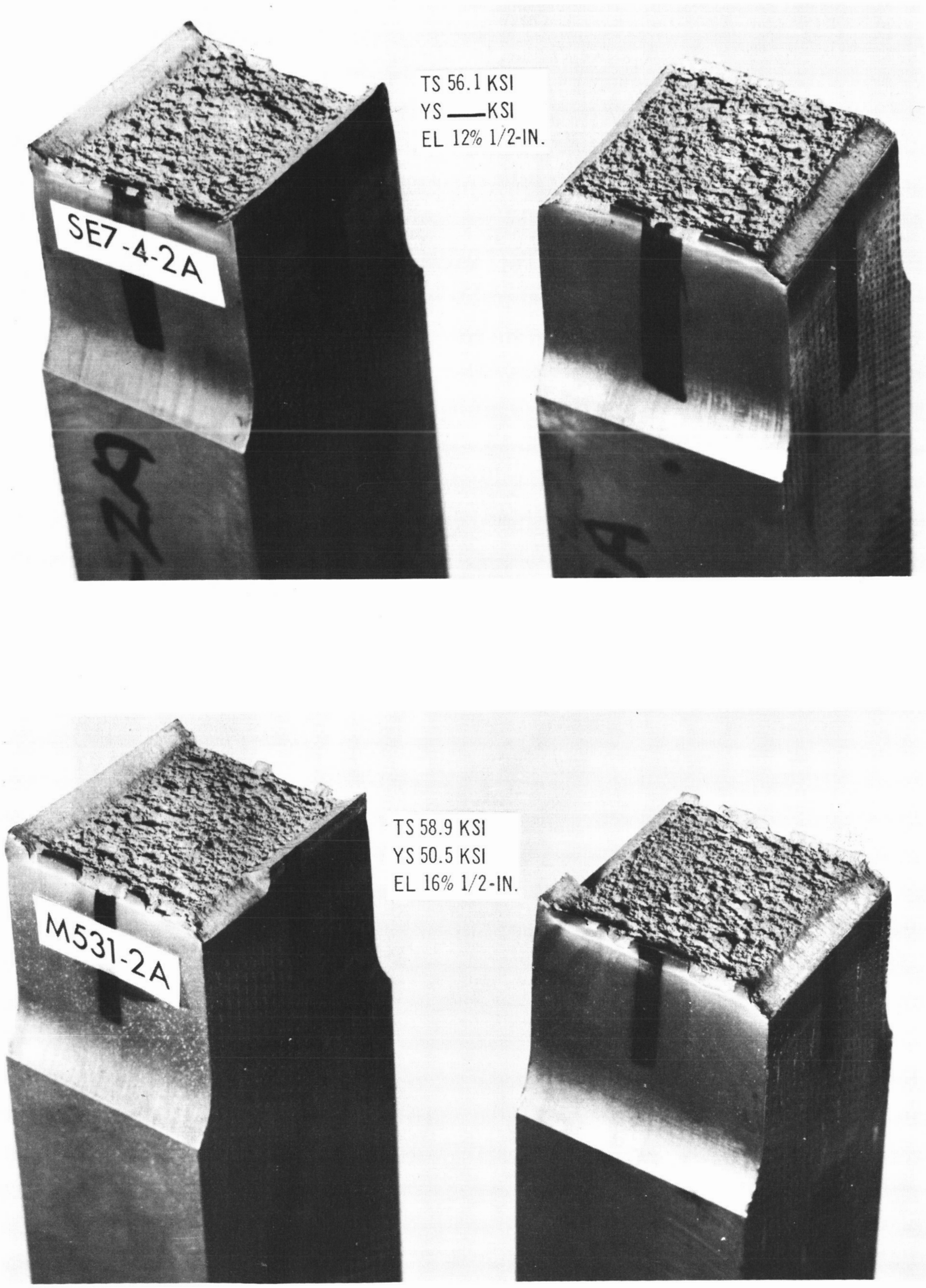
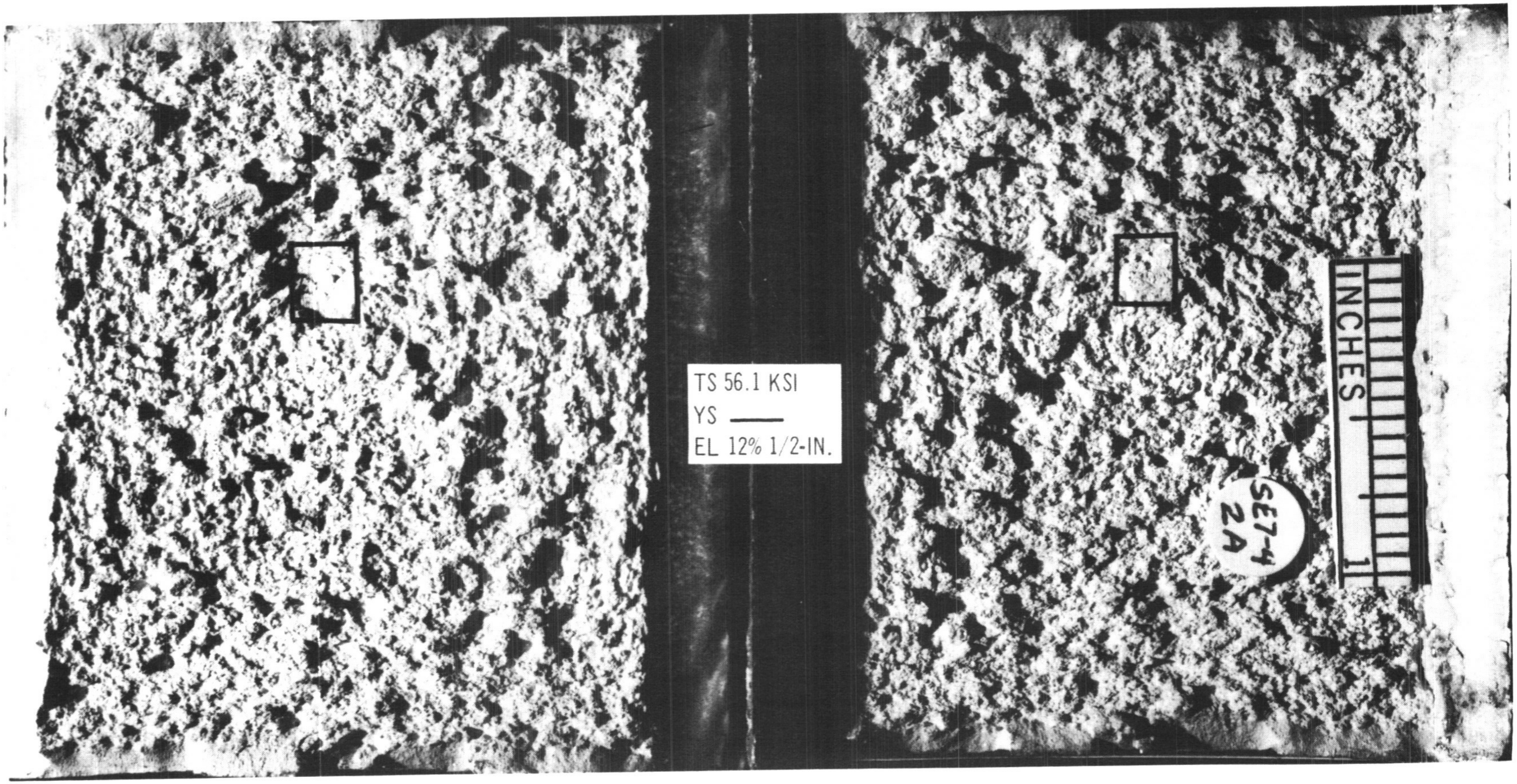
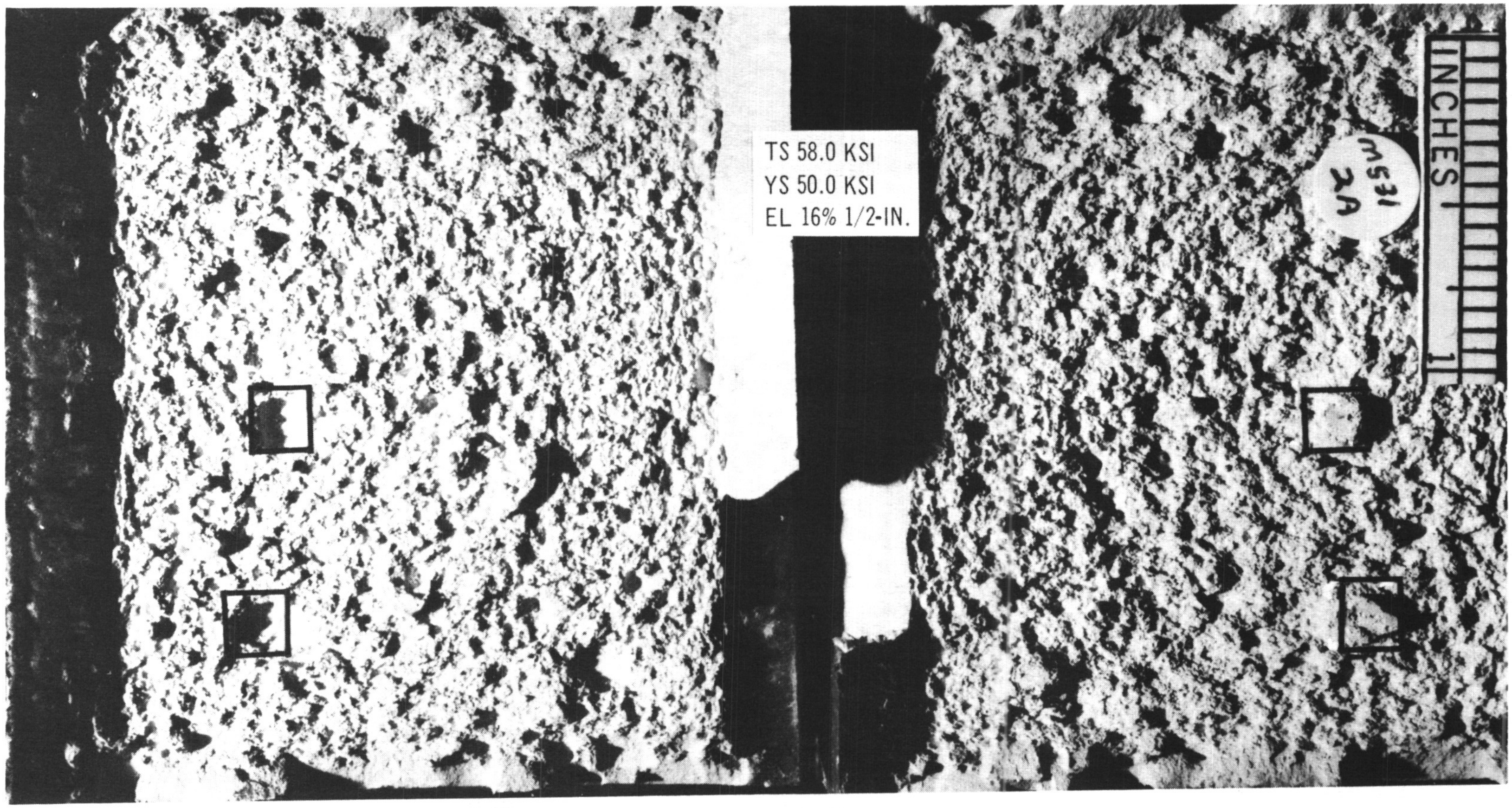


FIGURE 17. FRACTURED FULL THICKNESS TENSILE SPECIMEN IN 2-3/8-IN. THICK EB WELDED 2219 PLATE.



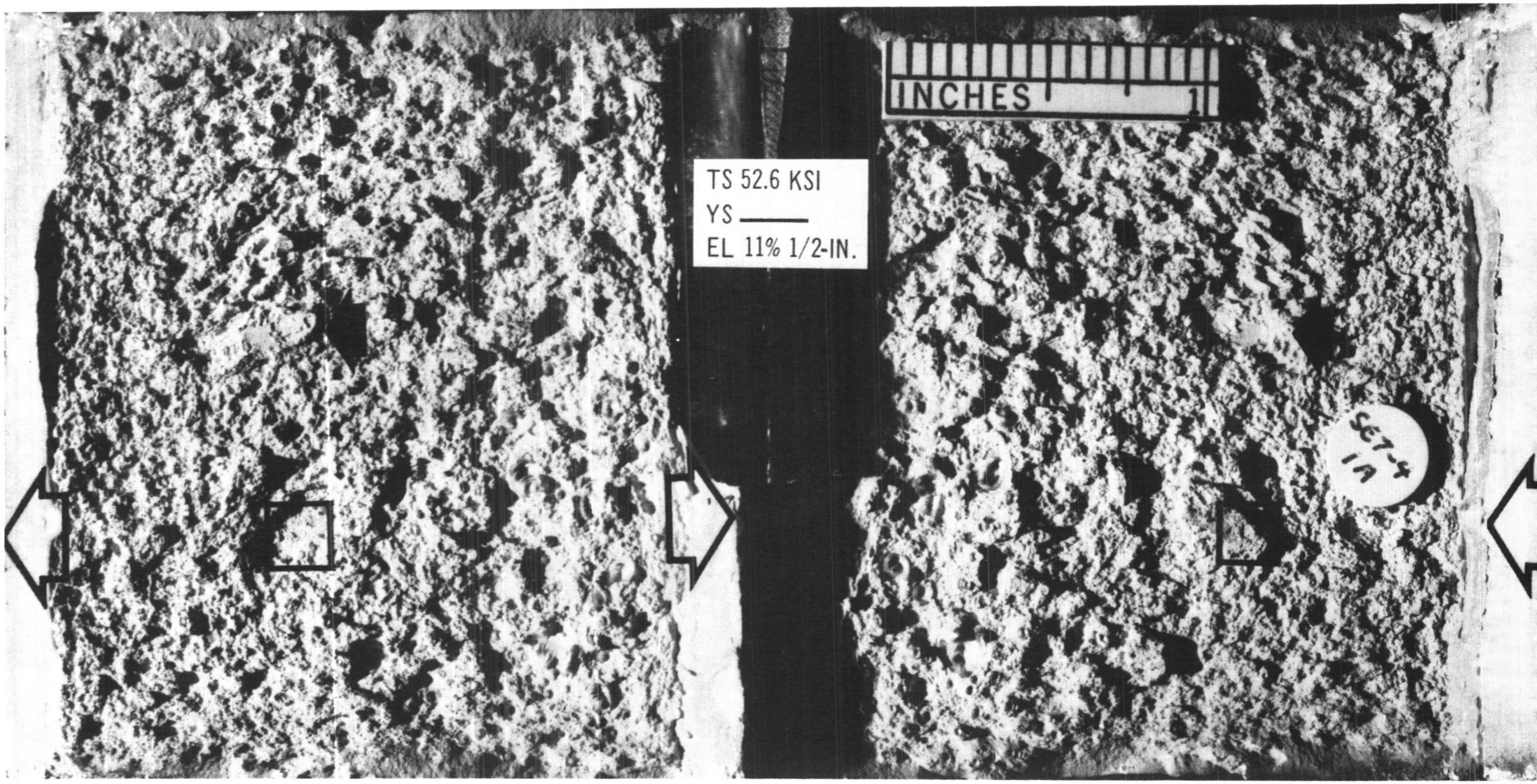
FACE ROOT FACE

FIGURE 18. FRACTURE SURFACES OF 2-3/8-IN. THICK HIGH STRENGTH EB WELD. SOME POROSITY, ONE FLAT SPOT NEAR CENTER.



FACE ROOT FACE

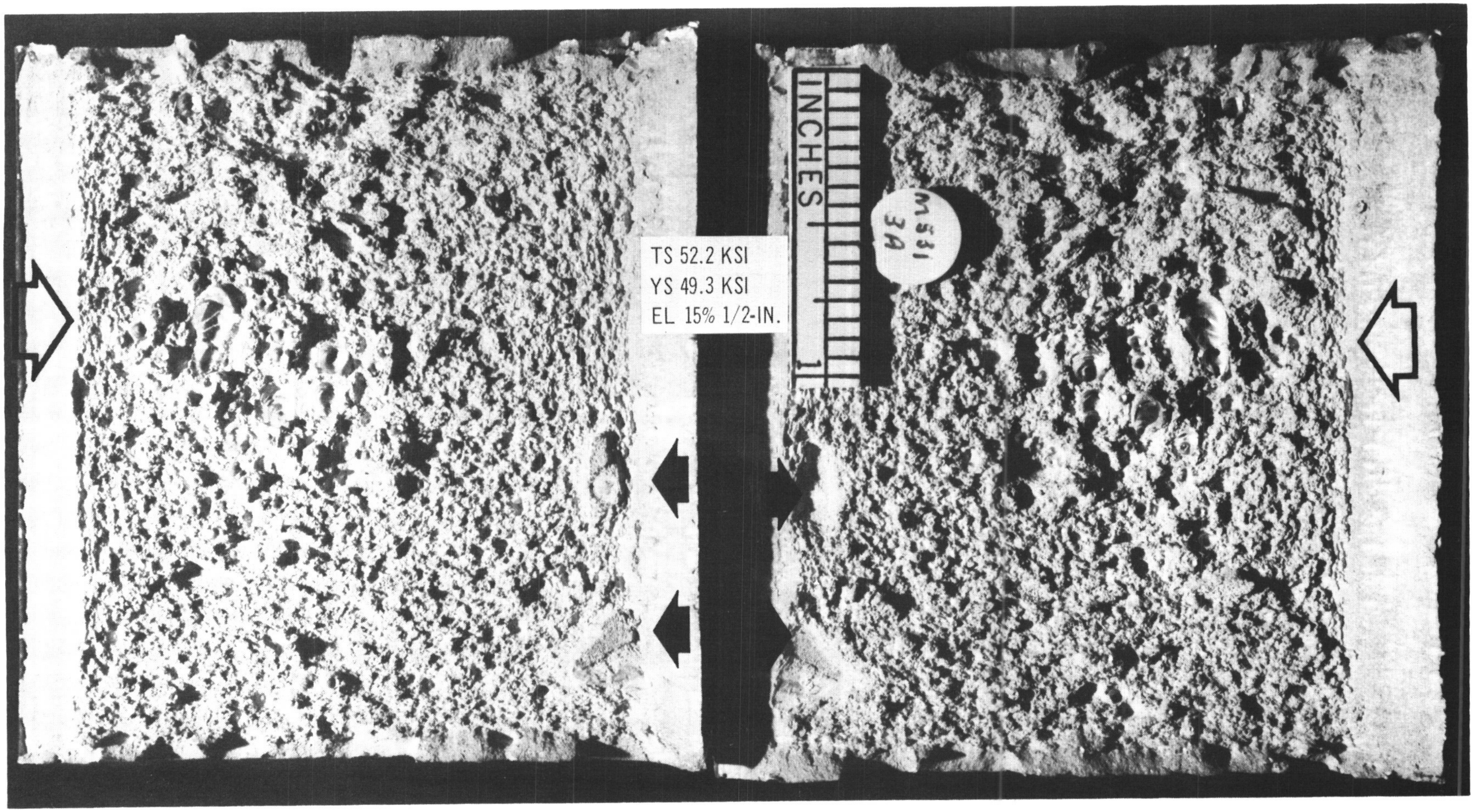
FIGURE 19. FRACTURE SURFACES OF 2-3/8-IN. THICK HIGH STRENGTH EB WELD. SOME POROSITY, TWO FLAT SPOTS NEAR FACE.



FACE ROOT FACE

NOTE: LARGE POROSITY BOTTOM THIRD, POROSITY AND FLAT SPOT IN LINE WITH DEPRESSION IN SURFACE BEADS (OPEN ARROWS, SEE FIGURES 4 AND 5), ONE NON-FUSED AREA (SOLID BLACK ARROW) NEAR CENTER.

FIGURE 20. FRACTURE SURFACES OF 2-3/8-IN. THICK LOW STRENGTH EB WELD.



FACE ROOT FACE

NOTE: LARGE POROSITY (OPEN ARROW) AND TWO NON-FUSED AREAS AT ROOT (SOLID BLACK ARROWS).

FIGURE 21. FRACTURE SURFACES OF 2-3/8-IN. THICK LOW STRENGTH EB WELD.

Tensile specimens from the tapered Y-configuration, machined as shown in Figure 22, also exhibited "flat" spots and non-fused spots toward the root side as illustrated in Figure 23. This specimen developed a TS of 53.5 ksi. No porosity was observed in the specimens from the stem of the Y.

Current speculation on the nature or cause of "non-fused" spots relate them to (1) a collapsed void and/or (2) entrapped oxide film. The fact that these defects have been observed consistently located at the edge of the weld gives credence to these possibilities in view of some early observations with problem areas in plate, heavy tapered sections, and a 5 inch block.

Electron Beam Welds

Low Voltage and High Voltage

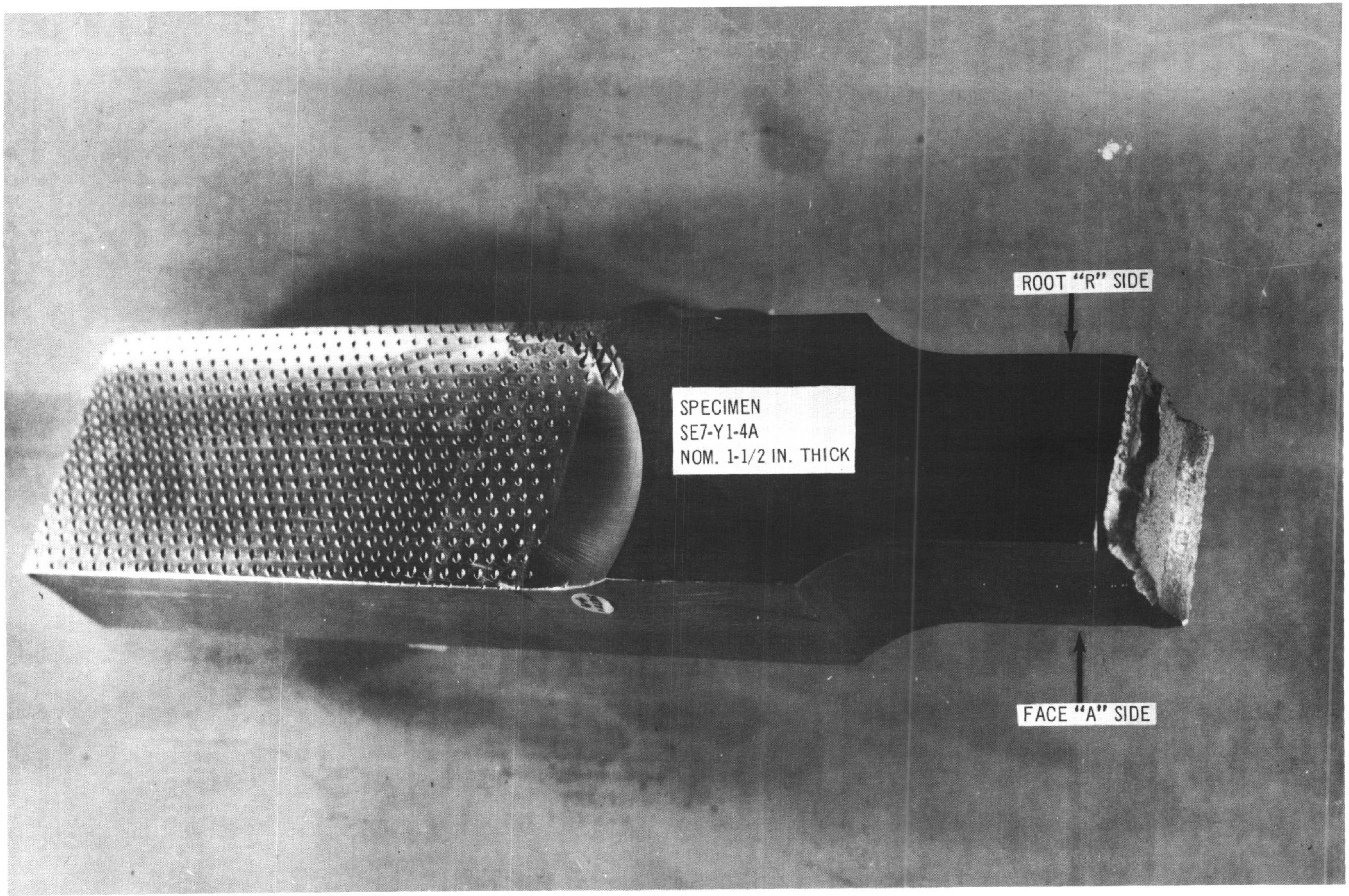
The preceeding data applies to welds made using low voltage type welders (Sciaky, 30KV). For comparison, data for welds made using a high voltage welder (Hamilton-Zeiss, 6KW) are presented in Table XI. The high voltage welded panels made by North American Aviation indicate that the 6KW welder may be limited to 1/2 inch or less in thickness for 2219 aluminum alloy and that for these gages strengths may not differ significantly from low voltage welds.

Electron Beam vs. TIG and MIG Welds

Strengths developed by EB welds, even those containing "defects", are generally higher than those developed by TIG or MIG welding. The high strength is based on efficient use of high density energy and the avoidance of appreciable heat absorbtion by the base metal. However, when less than desirable welding conditions are encountered in EB welding, strengths may be lowered to about the same level of other fusion welds as noted for the 0.31 inch and 0.25 inch gages in Table VIII. A comparison of TIG and EB weld configuration is shown in Figure 15.

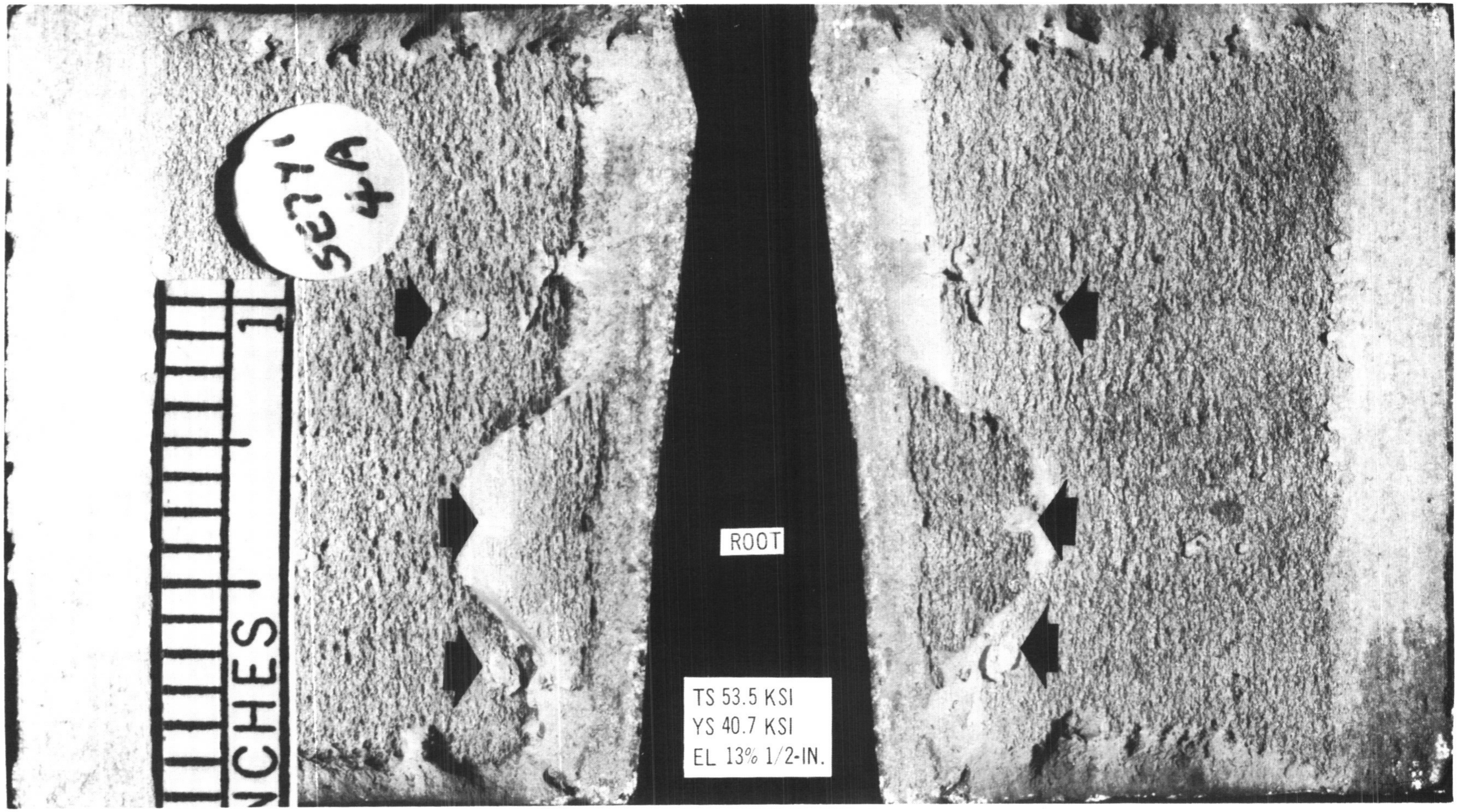
The following table gives a general comparison of TIG and MIG weld strengths (in the S-IC structure) with EB welds.

Location	Process	Thickness In.	TS ksi	TY ksi
Bulkhead to Y-Ring	MIG	.224	39	24
Circumferential Welds	TIG	.500	40	22
Y-Ring	EB	.500	47	32



NOTE: SHOWS TYPE OF SPECIMEN AND LOCATION OF FRACTURE.

FIGURE 22. FRACTURED FULL THICKNESS TAPERED SPECIMEN. NOMINAL 1-1/2 IN. THICK FROM Y.



FACE FACE

NOTE: SHOWS FLAT AREA AT ROOT AND SEVERAL NON-FUSED SPOTS TOWARD ROOT (SOLID BLACK ARROWS).

FIGURE 23. FRACTURE SURFACES. NOMINAL 1-1/2-IN. THICK FROM Y.

One of the most interesting indications with EB welding 2219 is that higher yield strengths are obtained with heavier gages than with the thinner material. This creates even greater interest and possible advantage for the EB process, considering the problems involved in heavier gage welding aluminum by the TIG and MIG processes and the resultant lower strengths developed. It has been demonstrated that EB parameters can be programmed for welding variable thickness and still develop high strengths even though settings might not be optimum for a given gage in that cross section.

CONCLUSIONS

1. Heavy gage aluminum alloy 2219 can be electron beam welded satisfactorily up through 2 3/8-inch thickness employing a high powered low voltage welding system.

2. Significantly higher strength and joint efficiency can be developed in plate gages by the EB process than by either TIG or MIG welding, i.e., TS efficiency 70 to 80 per cent for EB welds and 50 to 65 per cent for TIG and MIG. So called "Yield Strengths" for EB welds show an even more favorable situation.

3. Welding speed, power input, and other welding conditions affect penetration, weld geometry and strength. The most desirable weld profile appears to be narrow and parallel-sided. No difference in power requirement was noted for flat vs. vertical position welding.

4. A smoothingpass is usually required on the face and/or root side of the weld to overcome the rough hill-and-valley contour characteristic of EB welds.

5. Strengths vary with the type specimen employed. Full thickness tensile specimens provide more significant information than round or flat sheet-type tensile specimens from across the thickness.

6. Welds are quite ductile as evidenced by the measured reduction in area of 19 to 28 per cent on round tensile bars and by the necking of even the full thickness tensile specimesn. Good elongation has been exhibited by cast and wrought metal within 1/2 inches of the weld centerline.

7. The presence of porosity in electron beam welds is detrimental but has not shown as deleterious an effect on strength as was anticipated --- particularly considering the relatively narrow width of the cast metal.

8. Non-fused areas in heavy gage welds are associated with low strengths. These "defects" may be related to gun performance, weld turbulence, and thermal conditions at the root of the weld.

9. Gun arcing apparently may occur at any time but is more of a problem with heavy gage material.

10. Distortion encountered in thinner gage plate can be minimized by providing a parallel-sided weld profile.

11. Strength of Y-configuration varies with gage and location in the Y --- highest strengths being developed in the heavier gage areas of the stem and lower strengths in the thinner bulkhead leg where weld depth-to-width ratio is lower.

RECOMMENDATIONS

Our tensile tests to date on EB welded 2219 indicate the level of strengths that can be developed by a uniaxial specimen transverse to the weld. The following additional tests are suggested to provide a basis for a more comprehensive evaluation of joint performance of EB welds in aluminum.

1. Notch sensitivity - Ambient and cryogenic temperature notch vs. unnotch ratio, (a) notch in weld, (b) notch at interface.

2. Fatigue

3. Longitudinal tensile - Determine elongation in weld and parent metal at various locations from weld.

4. Biaxial tensile i.e., bulge of welded 1/4-inch or 1/2-inch thick plate. Radiographic standards need to be clarified for EB welds considering the narrow width of weld.

5. Radiographic standards --- clarification and refinement for EB welds, considering the narrow width of welds.

TABLE I

PROPERTIES OF 2219 PLATE

Temper	Gage	Tensile Properties TS ksi	YS ksi	El. % in 2"	Gas Content ml H_2 STP 100 gm Metal	ml Other 100 gm Metal
-T81	½"	65	48	12		
	1¼"	66	50	10		
	2-3/8"	67	50	9		
-T87	½"	68	56	10		
	3/4"	68	56	11		
-T87	½"	65	51	12	0.16	0.05
	3/4"	68	55	10	0.12	0.04
	1¼"	69	56	10	0.09	0.04
	2-3/8"	69	56	10	0.17	0.08

Temper	Gage	Actual Chemical Analysis Cu	Mn	Mg	Cr	Ti	V	Zr	Zn	Si	Fe
-T87	½"	6.06	.28	.00	.01	.06	.10	.17	.01	.08	.18
	3/4"	6.26	.27	.00	.01	.06	.10	.16	.01	.09	.18
	1¼"	6.18	.29	.01	.01	.05	.10	.16	.02	.09	.18
	2-3/8"	6.16	.17	.02	.01	.06	.11	.17	.02	.09	.17

TABLE II

WELD PARAMETERS EMPLOYED IN EB WELDING 2219 PLATE

Plate Gage	Gun MA	Weld Position	Beam KV	Beam MA	Beam ipm	Focus Amp	Filament Amp	Gun to Work	Power KW	Energy Kilojoules in.
Fusion Pass										
½"	500	flat	19.5-23.0	300-390	44-90	4.4-5.3	52-58	1¼-1½"	6.0-9.2	5.51-8.18
	500	Vertical Up	21.0-29.0	270-360	60-84	4.2-5.3	54-62	1¼-1-3/4	6.3-8.2	5.65-8.16
	1000		14.3	450	60	4.8	70	1½	6.4	6.43
3/4"	500	flat & VU	24.5-25.0	435-440	60	4.7-5.0	55-56	1¼	10.7-11.0	10.66-11.00
	1000	VU	18.9	520	43	4.2	70	1½	9.8	13.7
1"	500	flat	27.5	475	60	5.0	55	1¼	13.1	13.06
1¼"	1000	VU	23.2-25.0	700-775	43	4.3-4.6	68	1½	16.7-19.4	23.3-27.03
2-3/8"	1000	VU	30	1000-1100	43	4.4-4.8	70	1¼-1½	30-33	41.9-46.0
Smoothing Pass										
½-1"	500	flat or VU	10-14	110-200	21-30	3.0-5.1	52-60	1¼-1-5/8	---	---
3/4-2-3/8"	1000	VU	10-11.7	220-300	21	2.5-5.4	68-70	1¼-1½	---	---

TABLE III

SETTINGS AND TENSILE PROPERTIES FOR EB WELDED 2219 PLATE

WELDED IN FLAT POSITION

IN SCIAKY LAB CHAMBER

Plate		Beam				Focus	Filament	Gun to
Temper	Gage	KV	MA	ipm	KW	Amp	Amp	Work/In.
-T81	½"	20.0	300	44	6.0	5.3	58	1½"
↓	↓	23.5	390	90	9.2	5.1	55	↓
-T87	½"	19.5	340	60	6.6	4.4	54	1½"
	3/4"	24.5	435	60	10.7	4.7	55	
↓	1"	27.5	475	60	13.1	5.0	55	↓

		Kilojoules in./in.	Smooth Pass	Specimen Width	No. Specs.	TS ksi	YS ksi	El. % in 1"	El. % in 2"
-T81	½"	16.36	None	1-3/16"	(1)	49	36	---	9
↓	↓	12.26	↓	↓	(1)	54	38	---	8
-T87	½"	13.26	Face	1/8" Slice from 6x6" panels	M398 (3)	43	32	3.7	1.8
	3/4"	14.21			M393 (3)	43	33	4.0	2.0
↓	1"	13.06	↓	↓	M390 (3)	42	34	2.7	1.3

TABLE IV

WELD SETTINGS FOR EB WELDED 2219 PLATE---WELDED VERTICALLY UP
IN SCIAKY LAB CHAMBER

Plate		Beam				Focus	Filament	Gun to	Kilojoules
Temper	Gage	KV	MA	ipm	KW	Amp	Amp	Work/In.	In./In.
Fusion Pass									
-T87	½"	a 21.5	370	62	7.7	4.2	56	1½	14.94
	3/4"	a 25.0	440	60	11.0	5.0	56	1½	14.67
	↓	18.9	520	43	9.8	4.2	70	1½	18.30
-T81	1½"	23.2	720	43	16.7	4.3	70	1½	18.64
	2-3/8"	30.0	1000	43	30.0	4.8	70	1½	17.62
Smoothing Pass (Face and Root)									
-T87	½"	a 12	160	21	1.9	3.1	56	1½	
	3/4"	a 12.5	160	30	2.0	3.0	56	1½	
	↓	10	240	21	2.4	2.8	70	1½	
-T81	1½"	10	230	21	2.3	2.8	70	1½	
	2-3/8"	10	220	21	2.2	2.8	70	1½	

a = 500 MA Gun, others = 1000 MA Gun

TABLE V

TENSILE PROPERTIES OF EB WELDED 2219 PLATE

WELDED VERTICALLY UP---6 X 6" PANELS

IN SCIAKY LAB CHAMBER

Temper	-T87						-T81					
Gage	1/2"			3/4"			1¼"			2-3/8"		
	TS ksi	YS ksi	El.% 2"	TS ksi	YS ksi	El.% 2"	TS ksi	YS ksi	El.% 2"	TS ksi	YS ksi	El.% 2"
Plate Properties												
Plate	68	56	10	68	56	11	66	50	10	67	50	9
Weld Properties												
Slice Width .090"	41 (6)	31	2.2	41 (6)	33a 32b	2.8	40 (6)	--	2.7	40 (5)	--	2.7
.250"	46 (6)	32	3.0	46 (6)	36a 32b	3.3	45 (6)	--	3.0	44 (5)	--	3.7
.500"	48 (6)	--	3.2	49 (4)	--	3.5	48 (6)	--	3.4	47 (4)	--	3.7
Round			1"			1"			1"			1"
¼" Dia.	43 (4)	27	5.2	a43 (2) b41 (2)	26 25	5.0 6.0	42 (4)	25	5.0	41 (9)	24	4.4
			RA 28			RA 30			RA 22			RA 22

a = 500 MA Gun, 60 ipm, 11 KW, 14.67 Kilojoules in./in.

b = 1000 MA Gun, 43 ipm, 9.8 KW, 18.30 Kilojoules in./in.

RA = Reduction in Area in %.

○ Encircled No. = No. of Specimens

TABLE VI

WELD SETTINGS AND TENSILE PROPERTIES OF EB WELDED 2219-T87 PLATE

WELDED VERTICALLY UP - 36" X 20" PANELS

IN SPLIT CHAMBER

Plate Gage	½"				1¼"				2-3/8"			
	Beam				Beam				Beam			
Weld Settings	KV	MA	ipm	KW	KV	MA	ipm	KW	KV	MA	ipm	KW
Fusion Pass	a 23 14	355 450	60 60	8.1 6.4	25	775 700	43	19.4 17.5	30	1100	43	33
Smooth Pass	a 14	200	21	2.8	11.7	260 300	21	3.0 3.5	11.7	300	21	35
	TS ksi	YS ksi	El. % in ½"	El. % in 2"	TS ksi	YS ksi	El. % in ½"	El. % in 2"	TS ksi	YS ksi	El. % in ½"	El. % in 2"
Plate Props.	65	51	--	12.5	69	56	--	10.5	70	57	--	10.2
Welds ¼, ½" Dia.[b]	(12) 43	27	10	--	(8) 45	30	14	3.4	(17) 46	32	12	3.0
.5 x .5" Flat[b]	(3) 47	29	15	3.8	(15) 46	32	11	3.5	(12) 45	33	11	2.8
Full Section[c]	(12) 47	32	15	3.8	(12) 51	40	15	4.7	(6) 55	51	12	4.7

a = 500 MA Gun, all others 1000 MA Gun.

b = Specimens from Center, Face and/or Root of Welded Plate Thickness.

c = Specimen 1½" Wide in Gage for ½ and 1¼" Thick Plate and 2½" Wide for 2-3/8" Plate.

○ Encircled No. = No. of specimens.

TABLE VII

TENSILE PROPERTIES ACROSS THE THICKNESS OF 2-3/8" THICK 2219-T87 PLATE AND ELECTRON BEAM WELDED PLATE

Location In Gage	TS ksi	YS ksi	El. % in 2"	El. % in .5"	TS ksi	YS ksi	El. % in 4 D.	El. % in .5"
Plate 2-3/8"	.3" thick, sheet-type spec.				1/8" dia. tensile spec.			
Surface	70	57	11	--	71	56	13	--
Mid-Center	68	55	10	--	69	55	13	--
Center	68	55	9	--	66	53	13	--
Mid-Center	69	55	10	--	68	54	11	--
Surface	70	56	10	--	71	56	13	--
2 Panels: M531 and SE7-4								
Welds 2-3/8"	.5" thick, sheet-type spec.				1/2" dia. tensile spec.			
Face	(4) 47 $\frac{45}{48}$	32	3	12	--	--	--	--
Near Face	--	--	--	--	(5) 46 $\frac{45}{47}$	32	3	13
Center	(4) 46 $\frac{46}{48}$	33	3	11	(6) 44 $\frac{40^{b}}{47}$	31	3	12
Near Root	--	--	--	--	(6) 46 $\frac{41c}{49}$	33	3	12
Root	(4) 43 $\frac{39^{a}}{45}$	33	3	11	--	--	--	--

a = Non-fused area.

b = Oxide spot.

c = Void, splash.

○ Encircled No. = No. of Specimens.

MWB
7-23-64

TABLE VIII

TENSILE PROPERTIES OF EB WELDED 2219-T81 VARIABLE THICKNESS "Y" CONFIGURATION PANELS

Location in "Y"	Spec. No.	Weld SE7-Y1 and M578-9							Weld SE7-Y6 and -Y7								Parent Metal			
		Nom. Thick.	TS ksi	YS ksi	*El.%(face)in ¼	½	1	2"	Nom. Thick.	TS ksi	YS ksi	*El.%(face)in ¼	½	1	2"	TS% Eff.	Nom. Thick.	TS ksi	YS ksi	El.% 2"
Stem	1A	0.74"	49	35	6	15	9	5	0.85"	50	38	7	14	9	5	--	--	--	--	--
			51	37	-	10	7	4		48	35	20	13	9	5	73.0	0.82"	67	53	10
	2A	0.84"	51	38	6	13	8	4	0.99"	51	41	2	14	10	5					
			51	--	-	11	7	4		49	37	8	17	10	6					
	3A	1.0"	52	39	6	13	9	4	1.1"	52	36	12	17	11	6					
			53	40	-	10	6	4		50	36	29	17	11	6					
	4A	1.2"	53	41	6	13	9	5(1)	1.4"	52	37	2	16	10	6	--				
			53	40	-	13	8	5		54	35	8	16	11	7	80.6				
	5A	1.5"	54	41	6	13	8	5(1)	1.7"	51	36	4	14	11	6					
			54	44	-	13	8	5		52	35	6	18	12	7					
Interstage Leg	7A	0.90"	48	36	14	11	7	4(1)	0.86"	50	33	9	18	13	6	--	---	--	--	--
			52	38	8	17	10	5		48	34	6	14	9	5	72.0	0.86"	67	55	12
Crotch Area	6A1	Y6 Only				4" Wide			0.73"	49	31	3	13	10	5	72.8	0.73"	67	52	15
(Bulkhead	6A2	↓				↓			0.52"	37	34	24	15	9	4(5)	59.5	0.52"	63	49	15
(Side	1G					½" Wide			0.53"	48	34	--	15	9	4	76.2	0.52"	63	49	15
Bulkhead Leg	8A	0.34"	44	27	20	14	8	5(2)	0.47"	41	33	17	12	7	4(6)					
			47	29	--	14	7	4		45	32	26	16	9	4					
	1E	0.31"	38	26	7	9	6	3(2)	0.40"	45	30	20	13	7	4(4)	69.0		65	51	12
			45	30	20	12	6	3(3)		42	30	18	12	6	3(3,6)	65.0	0.40"	64	51	10
	9A	0.25"	--	--	--	-	-	-(2)	0.29"	42	29	24	14	8	4					
			39	25	--	16	6	3		39	28	21	14	8	4(7)					

A=1½" Wide in Gage, E=½" Wide in Gage.
(1) Several spots on fracture, ? non-fused dots.
(2) Overheated, smoothing pass at ½ speed by error.
(3) Machined on face side.
(4) Machined on Root Side.

*Measured on face of weld (values different for edge and root esp. in 1/4 and 1/2" gage lengths).
(5) Considerable porosity at root adjacent V-block.
(6) Question of good fusion per vis. of fracture.
(7) Defective? fusion 3/8" on root, ?beam off-center of joint.

TABLE IX

8-17-64

TENSILE PROPERTIES OF EB WELDED 2219-T81 "Y"-RING VS. "Y"-PANELS

Location in "Y"	Spec. No.	W2 and W3 Welds from Y-Ring							SE7-Y6 and -Y7 Panels						
		Nom. Thick.	TS ksi	YS ksi	El. % (face) in ¼	½	1	2"	Nom. Thick.	TS ksi	YS ksi	El. % (face) in ¼	½	1	2"
Stem ↓	1A	0.87"	52	35	7*	12	10	7.5	0.85"	50	38	7*	14	9	5
		0.86"	52	37	2*	11	8	7.0		48	35	20	13	9	5
	2A	1.02"	52	36	6*	11	8	8.0	0.99"	51	41	2*	14	10	5
		1.01"	53	39	9*	15	10	8.0		49	37	8*	17	10	6
	3A	1.17"	55	38	10*	18	19	8.0	1.1"	52	36	12*	17	11	6
		1.18"	55	39	8*	14	10	8.0		50	36	29	17	11	6
	4A	1.47"	50	33	5*	18	13	8.5	1.4"	52	37	2*	16	10	6
		1.48"	53	40	5*	17	12	8.0		54	35	8*	16	11	7
	5A	1.80"	51	38	20	15	10	7.0	1.7"	51	36	4*	14	11	6
		1.80"	53	37	8*	10	11	9.0		52	35	6*	18	12	7
Interstage Leg	7A	0.87"	52	34	8*	15	10	8.5	0.86"	50	33	9*	18	13	6
		0.90"	51	35	--	17	11	8.0		48	34	6*	14	9	5
Bulkhead Leg ↓	8A	0.44"	44	30	3*	15	9	6.5	0.47"	41	33	17	12	7	4
		0.46"	42	25	3*	18	11	5.5		45	32	26	16	9	4
	9A	0.31"	43	29	4*	16	9	5.5	0.29"	42	29	24	14	8	4
		0.31"	44	--	5*	17	11	7.0		39	28	21	14	8	4

* = Failed outside gage marks.

TABLE X

DUCTILITY OF EB WELDED 2219-T87 PLATE

Plate Gage	Spec. Loc.	Guided Bend Test[a] Load psi	Angle Bend °	El. % in ¼	½	1	2"	Full Thickness Tensile	El. % in 1/8	¼	½	1	2"	Round Tensile Specimen Spec. Dia.	El. % in 1/8	¼	½	1	2"	Redn. Area %
¼"	face	(4) 5413	19.5	16	10	6	3	(12)	--	--	15	8	4	¼" (12)	20	16	10	4	--	24
	root	(4) 5444	19	14	9	5	2		--	19	13	7	3	(4)*	--	19	10	5	--	28
	edge	----	--	--	--	-	-		26	18	11	7	4							
3/4"	face	----	--	--	--	-	-	(4)	--	16	11	6	3	¼" (4)*	--	20	10	5	--	30
	edge	----	--	--	--	-	-		--	18	11	6	3							
1¼"	face	(4) 5349	20	13	8	6	3	(12)	--	--	12 15	10	5	½" (8)	23	21	14	7	3	26
	root	(4) 5272	14	10	6	3	2		--	--	(8) 13	9	5							
	edge	(1) 2490	15	13	7	5	3		(2) 26	(8) 19	(8) 14	(8) 9	(8) 4							
2-3/8"	face	----	--	--	--	-	-	(6)	--	--	(6) 12	9	5	½" (17)	24	19	12	7	3	22
	root	----	--	--	--	-	-		--	--	(6) 13	8	4							
	edge	----	--	--	--	-	-		(4) 22	(5) 17	(6) 13	(6) 9	(6) 5							
Y-Taper	face	----	--	--	--	-	-	max.	--	--	15	9	5	--	--	--	--	-	-	--
(.31" to	root	----	--	--	--	-	-	max.	--	--	15	9	5							
1.5")	edge	----	--	--	--	-	-	max.	25	22	15	8	5							

a = Bent over 1.5" radius until max. load obtained and "yielded," then unloaded.

Encircled No. = No. of Specimens.

* = From 6 x 6" Panels

TABLE XI

TENSILE PROPERTIES OF HIGH VOLTAGE EB WELDED 2219-T31 AND -T87 PANELS

WELDS* MADE BY NORTH AMERICAN AVIATION, INC. ON CONTRACT NAS8-11085
HAMILTON ZEISS 6 KILOWATT EB WELDER

Plate Gage	Plate Temper	Fusion Pass Beam KV	Fusion Pass Beam MA	Fusion Pass Beam ipm	Fusion Pass Beam Dia. in.	Fusion Pass Circ. Oscil. Dia.	Fusion Pass Focal Leng.	Fusion Pass Fila. Amp.	Fusion Pass Focus Amp.	Vacuum	Smoothing Pass Beam KV	Smoothing Pass Beam MA	Smoothing Pass Circ. Oscil. Dia.	Preheat Pass Beam KV	Preheat Pass Beam MA	Preheat Pass Oscil. Dia.
½"	-T81	140	20	16	.008	.010"	7"	1.6	.57	6-7 x 10^{-5}	120	10	.050"	-----	-----	------
↓	-T87	"	"	"	"	"	"	"	"	4-6 x 10^{-5}	"	"	"	-----	-----	------
1"	-T81	140	35	9	.008	.015"	7½"	1.65	.57	5-8 x 10^{-5}	120	10	.060"	120	5	.015"
↓	-T87	"	"	"	"	"	"	"	"	3-5 x 10^{-5}	"	"	"	"	"	"
1¼"	-T81	150	38	9	.008	---	6-3/4"	1.65	.59	5 x 10^{-5}	120	10	.080"	120	5	.015"

Plate Gage	Spec. Width	-T81 TS ksi	-T81 YS ksi	-T81 El. % in ½	-T81 El. % in 1	-T81 El. % in 2"	-T81 Power KW	-T81 Energy Kj/in.	-T87 TS ksi	-T87 YS ksi	-T87 El. % in ½	-T87 El. % in 1	-T87 El. % in 2"	-T87 Power KW	-T87 Energy Kj/in.
½"	½"	(10) 47	35	--	--	3.0	2.8	10.5	(10) 46	36	--	--	3.0	2.8	10.5
		(2) 49	37	15	10	5.3	"	"	(2) 48	38	14	8	5.0	"	"
1"	1½"	(8) 40	33	12	7	4.1	4.9	32.7	(8) 47	38	12	7	4.1	4.9	32.7
1¼"	1½"	(8) 36	(1) 35	11	7	4.0	5.7	38.0	--	--	--	-	---	---	---
For Comparison - Properties of Low Voltage Welded by Sciaky 30 KV Welder (No backing strip)															
½"	1½"	(1) 49	36	--	-	9.0	6.0	8.18							
↓	↓	(1) 54	38	--	-	8.0	9.2	6.13	(12) 47	32	15		3.8	8.1	8.1
1"	1/8"	--	--	--	-	---	---	---	(3) 42	34		2.7	1.3	13.1	13.1
1¼"	1½"	--	--	--	-	---	---	---	(12) 51	40	15		4.7	19.4	27.1

* Employed backing strip 1/8" thick x 3/8" wide.
() No. in parenthesis = No. of specimens tested.

BIBLIOGRAPHY

1. Brennecke, M. W., "Electron Beam Welded Heavy Gage Aluminum Alloy 2219", Welding Journal, 44 (1), Research Suppl. 27-s to 39-s.

2. Robeletto, R. P., Padian, W. D., and Clawson, D., North American Aviation, Inc., "High Voltage Electron Beam Welding of Aluminum Alloys", Final Report on NASA Contract NAS8-11085, dated 5/14/64. 99 pp.

3. Pfluger, Allan R., "Electron Beam Welding", Technical paper presented at 1964 Western Metal and Tool Conference, March 16, 1964, Los Angeles, California.

4. Fairbanks, R. H., and Adams, C. M., Jr., "Laser Beam Fusion Welding", Welding Journal, 43 (3), Research Suppl. 97-s to 102-s (1964).

5. Farrell, William J., "Electron Beam and Laser Techniques for Joining", Technical paper presented at 1964 ASM Golden Gate Metals Conference, January 1964, San Francisco, California.

6. Meier, J. W., "Recent Advances in Electron Beam Welding Technology", Welding Journal, 42 (12), 963-7 (1963).

7. Platte, W. N., and Smith, J. F., "Laser Techniques for Metals Joining", Ibid, (11), Research Suppl. 481-s to 489-s (1963).

8. Garibotti, D. J., and Lane, W. W., "Microminiature Electron Beam Welded Connections", Ibid (9), Research Suppl. 417-s to 427-s (1963).

9. Gurev, H. S., and Stout, R. D., "Solidification Phenomena in Inert Gas Metal-Arc Welds", Ibid (7), Research Suppl. 298-s to 310-s (1963).

10. Schillinger, D. E., Betz, I. G., Hussey, F. W., and Markus, H., "Improved Weld Strength in 2000 Series Aluminum Alloys", Ibid (6), Research Suppl. 269-s to 275-s (1963).

11. Barry, J. M., Paley, Z. V. I., and Adams, C. M., Jr., "Heat Conduction from Moving Arcs in Welding", Ibid (3), Research Suppl. 97-s to 104-s (1963).

12. Travis, R. E., Ardito, V. P., and Adams, C. M., Jr., "Comparison of Processes for Welding Ultra-High Strength Sheet Steels", Ibid (1), Research Suppl. 9-s to 17-s (1963).

13. Bakish, Robert (Editor), "Introduction to Electron Beam Technology", Chapter 9, White, S. S., and Bakish, Robert, "Electron Beam Welding", pp. 212-257, 1962, John Wiley and Sons, Inc., New York.

14. White, S. S., Lander, H. J., Hess, W. H., and Bakish, R., "Electron Beam Welding - A Study. Pt. I, Beryllium and Titanium Alloys. Pt. II High Strength Sheet Steels, Tungsten, Molybdenum and Heat Flow Determinations." Welding Journal 41 (6), Research Suppl. 279-s to 288-s and (7), 329-s to 336-s (1962).

15. Roth, R. E., and Bratkovich, N. F., "Electron Beam Weld Characteristics and Strength Data in Four Representative Materials", Ibid (5), Research Suppl. 229-s to 240-s (1962).

16. Aemisegger, E. R., and Nyenhuis, H. A., "Super-Depth Welds Made with a High Energy Density Electron Beam --- A Revolution in Welding", Ibid 40 (12), 1240-45 (1961).

17. White, S. S., "Experimental Determination of Dimensional Heat Flow in Weldments", Ibid (7), Research Suppl. 317-s to 319-s (1961).

18. Wells, O. C., p. 301 in Proc. Third Symposium on Electron Beam Technology, R. Bakish, Editor, Alloyd Corporation, Boston, 1961.

19. Meier, J. W., "Electron Beam Welding Characteristics of Several Materials", p. 145 in Ibid.

20. Rykalin, N. N., "Calculation of Heat Processes in Welding", Moscow, U. S. S. R., 1960.

21. Brown, P. E., and Adams, C. M., Jr., "Fusion-Zone Structures and Properties in Aluminum Alloys", Welding Journal 39 (12), Research Suppl. 520-s to 524-s (1960).

22. Burton, G., Jr., and Frankhouser, W. L., "Electron Beam Welding", Ibid 38 (10), Research Suppl. 401-s to 409-s (1959).

23. Nippes, E. F., "The Weld Heat-Affected Zone", Ibid (1), Research Suppl. 1-s to 18-s (1959).

24. Adams, C. M., Jr., "Cooling Rates and Peak Temperatures in Fusion Welding", Ibid 37 (5), Research Suppl. 210-s to 215-s (1958).

25. Michael, A. B., and Bever, M. B., "Solidification of Aluminum Rich Al-Cu Alloys", Trans. A. I. M. E., 200, 47-56 (1954).

26. Smith, C. O., Funk, E. R., and Udin, H., "An Analytical Study of Aluminum Welding", Welding Research Council Bulletin 12, (June 1952), American Welding Society, New York.

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Mr. Wilson
Mr. Williams
Miss Brennecke

R-ME-T
Mr. Franklin

MS-IP

Boeing Company
Michoud Operations
Mr. Bodner
Mr. Runkel
Mr. Stone